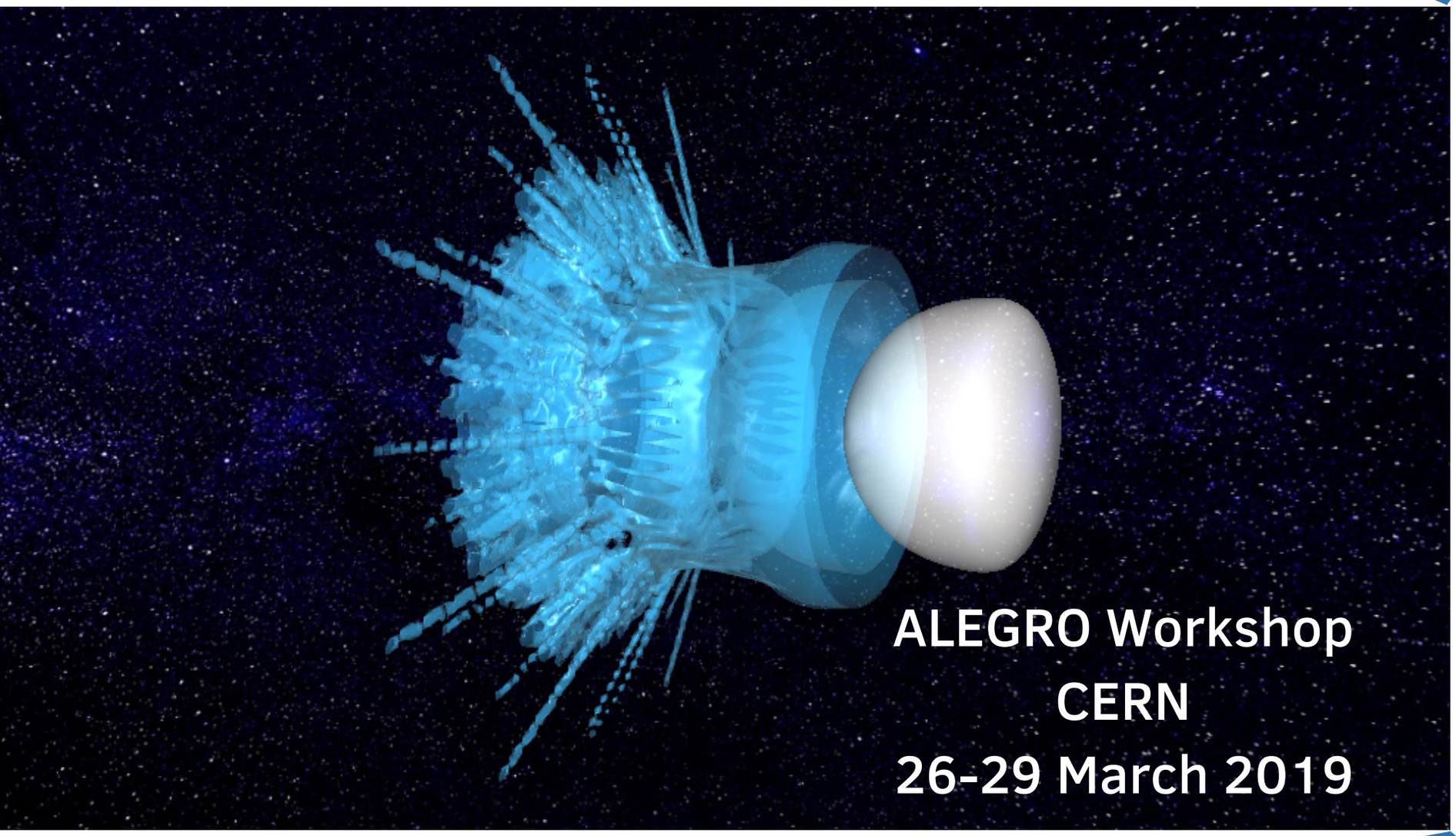
Simulations of Staging Experiments at Apollon



Francesco Massimo

Outline

- Context

- Modeling Laser Wakefield Acceleration with a laser envelope

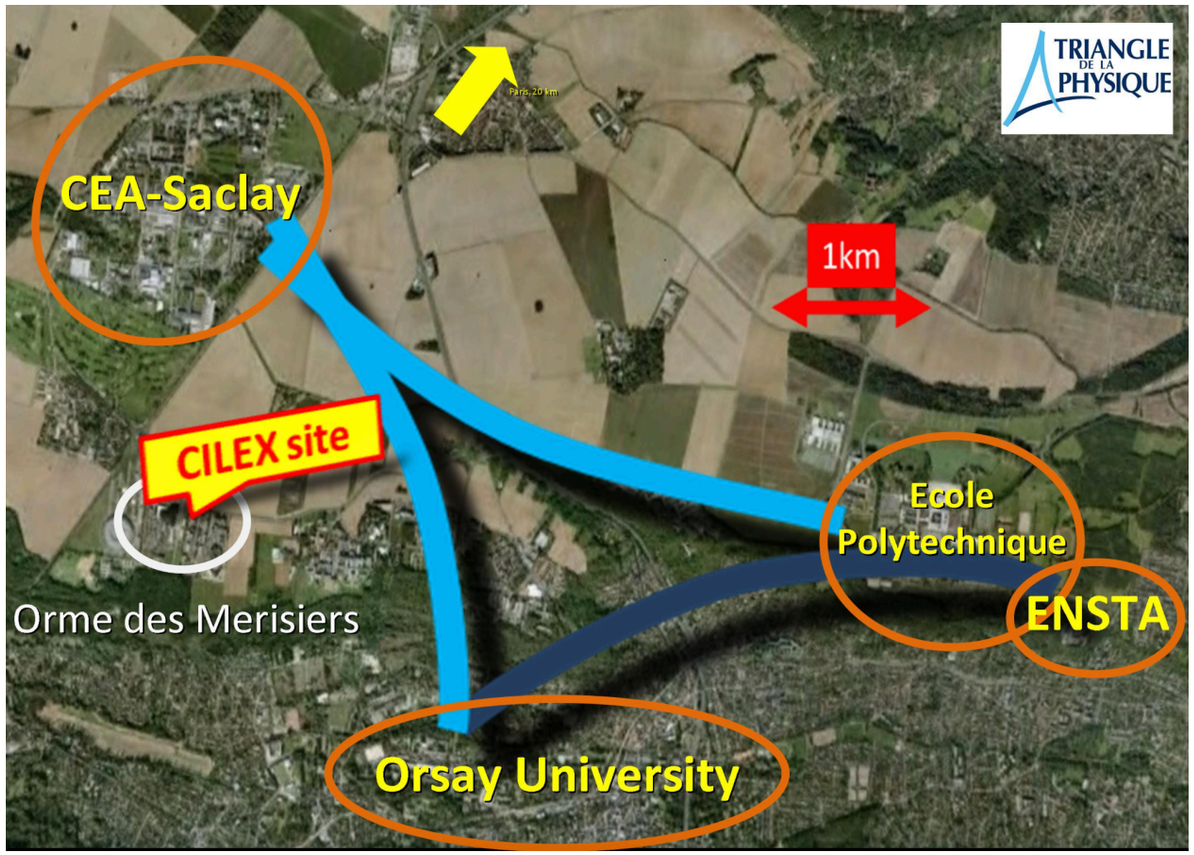
- First stage simulations

- Second stage simulations: Standard PIC vs Envelope PIC

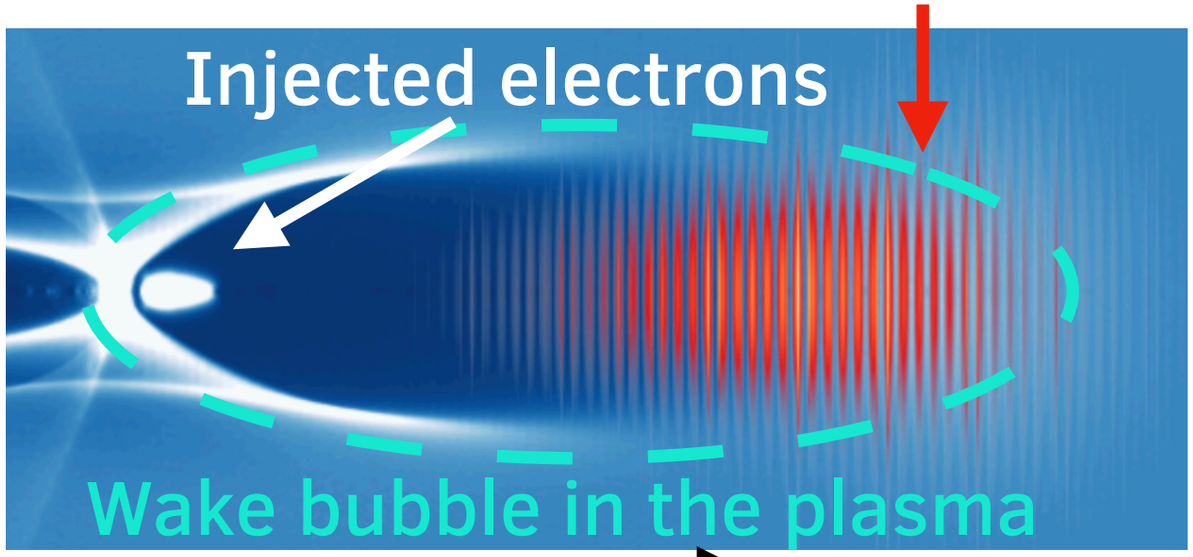
- Future steps for multi-stage simulation

Centre Interdisciplinaire de la Lumière Extrême (CILEX)

CilEX Apollon

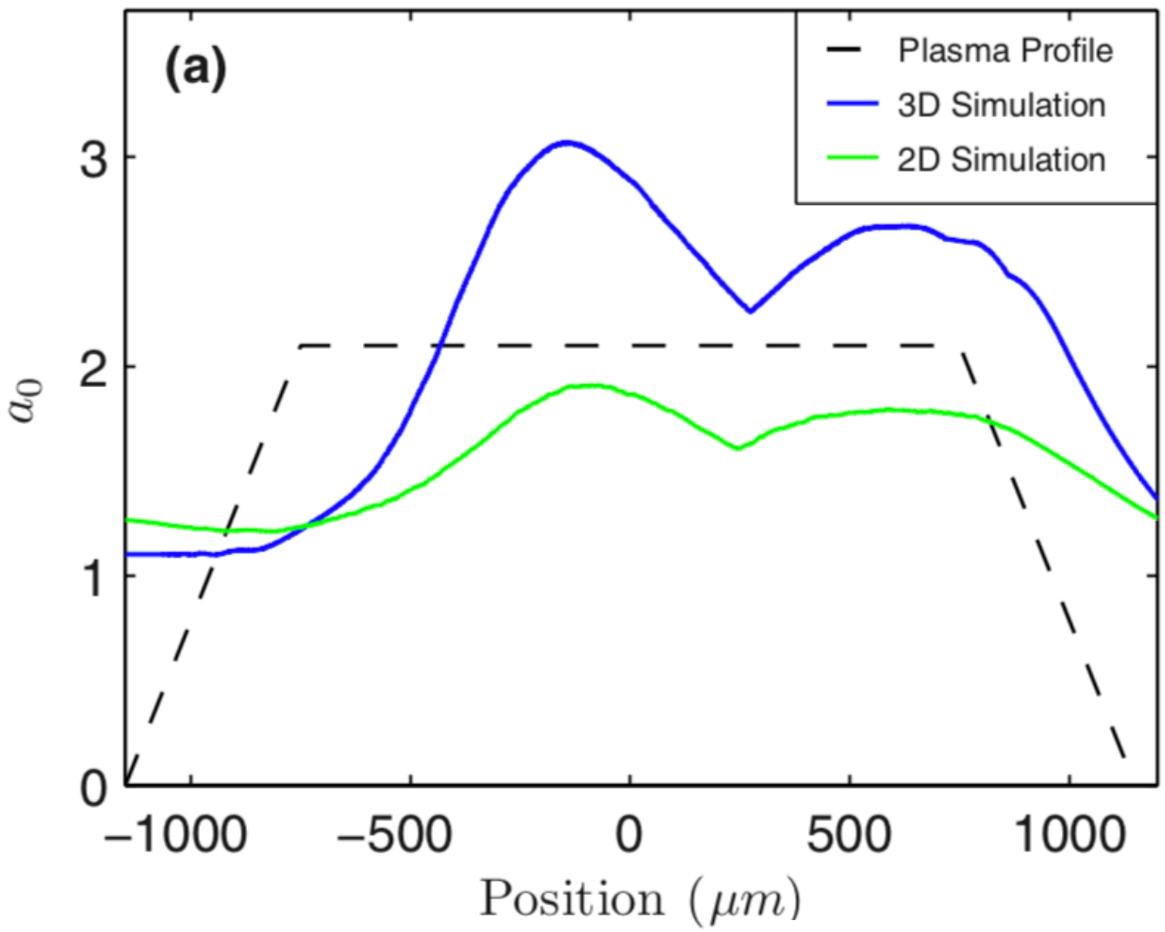


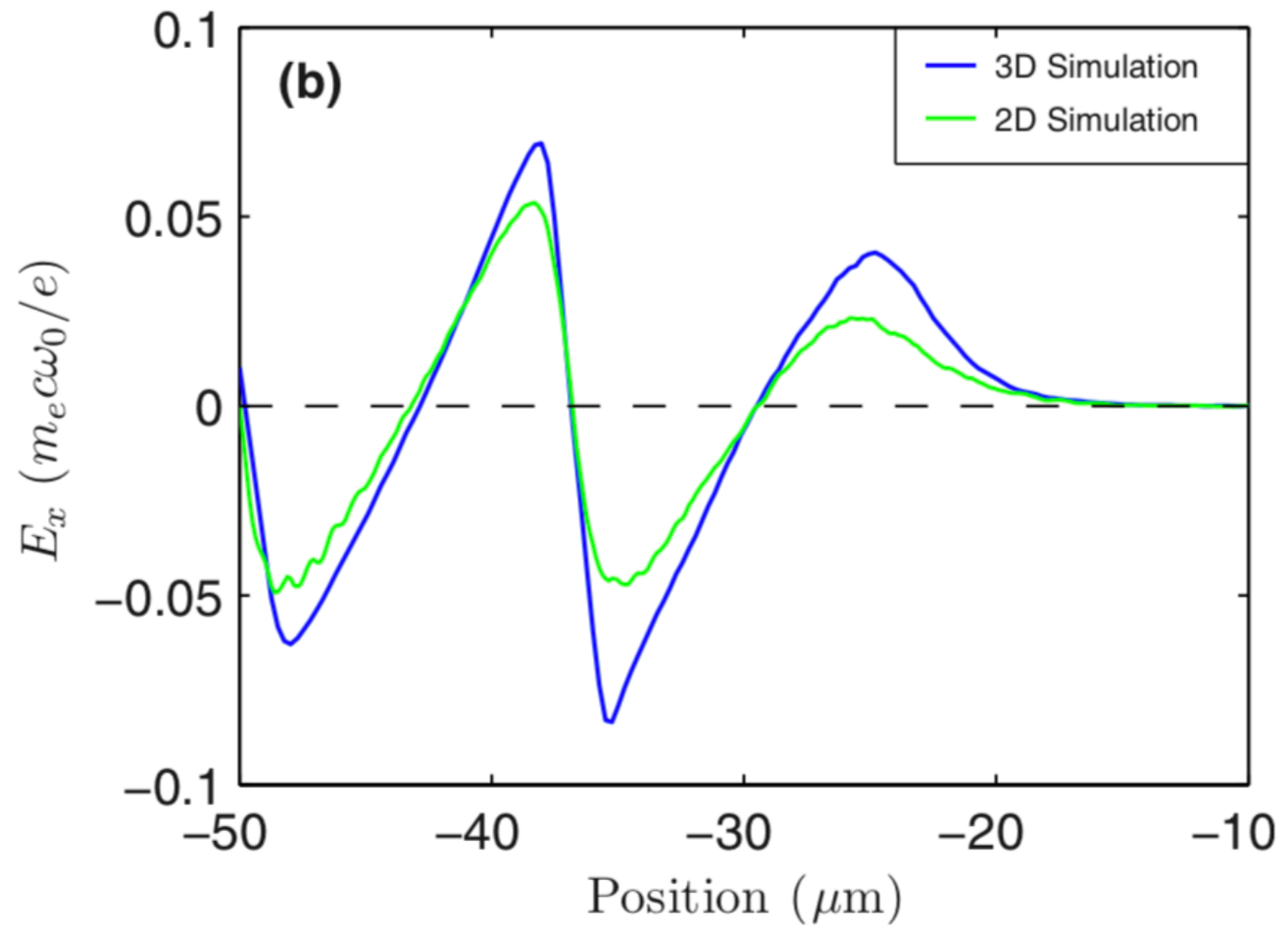
Laser Wakefield Acceleration (LWFA)



LWFA PIC simulations are cumbersome

X. Davoine, Physics of Plasmas 15, 113102 (2008)





2D cartesian simulations

are not accurate enough for LWFA!

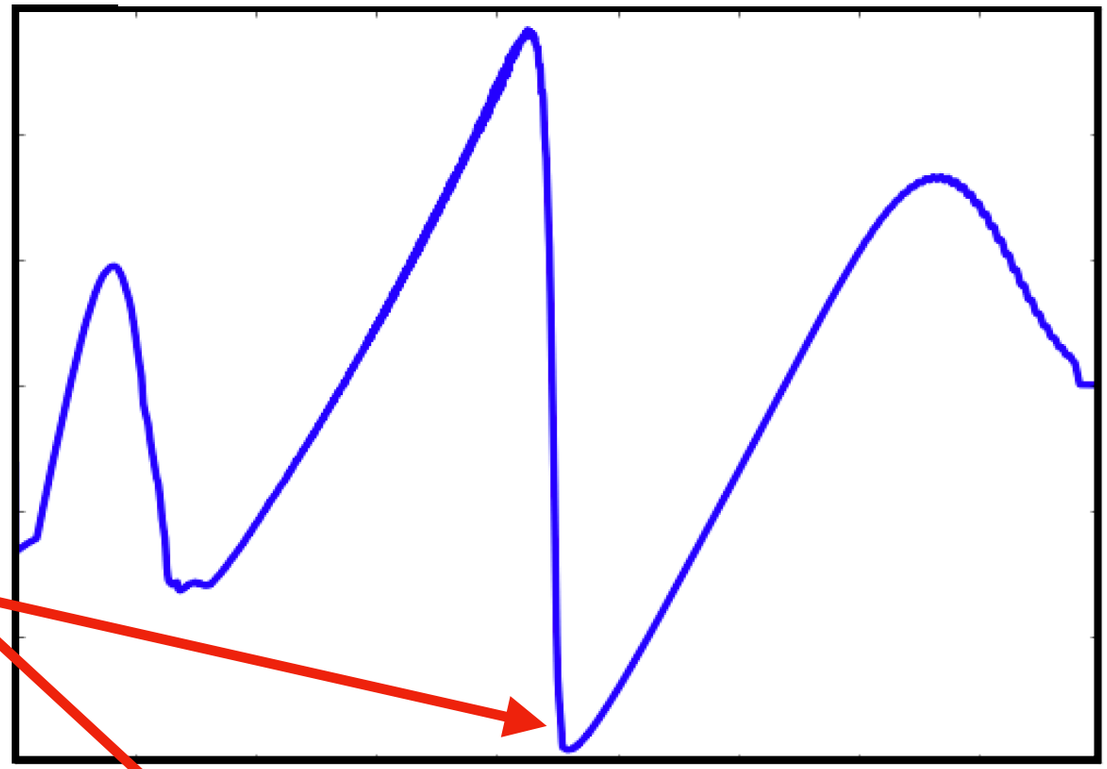
3D LWFA simulations:

1 mm plasma ~ 320 kcpu-hours ~ 10.2 k€

Laser Wakefield Acceleration (LWFA): Characteristic Scales

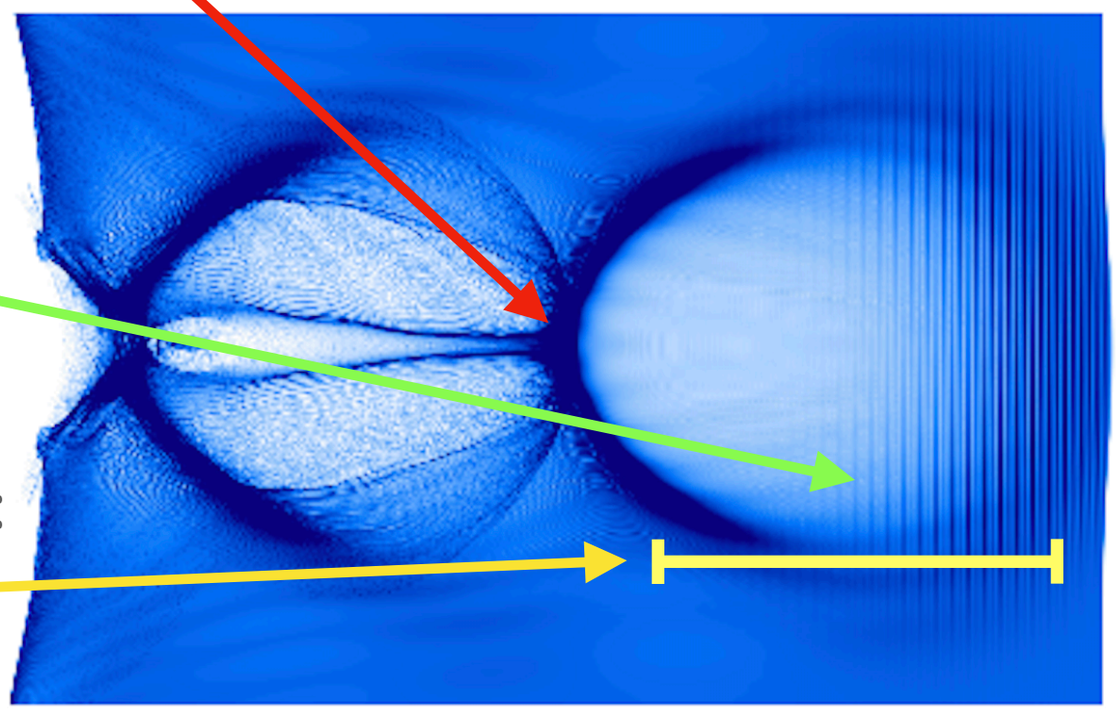
E > 100 GV/m

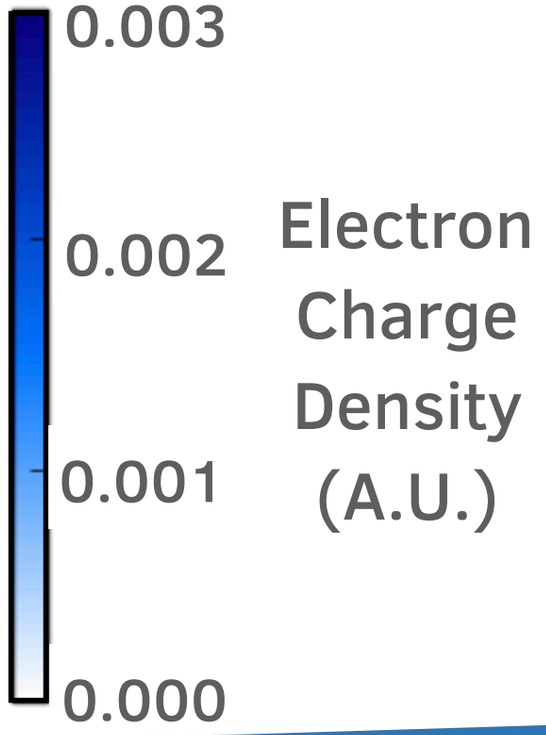
Electrons injected here are accelerated



Laser wavelength: ~1 μm

Laser duration ~ Plasma wavelength: ~20 μm

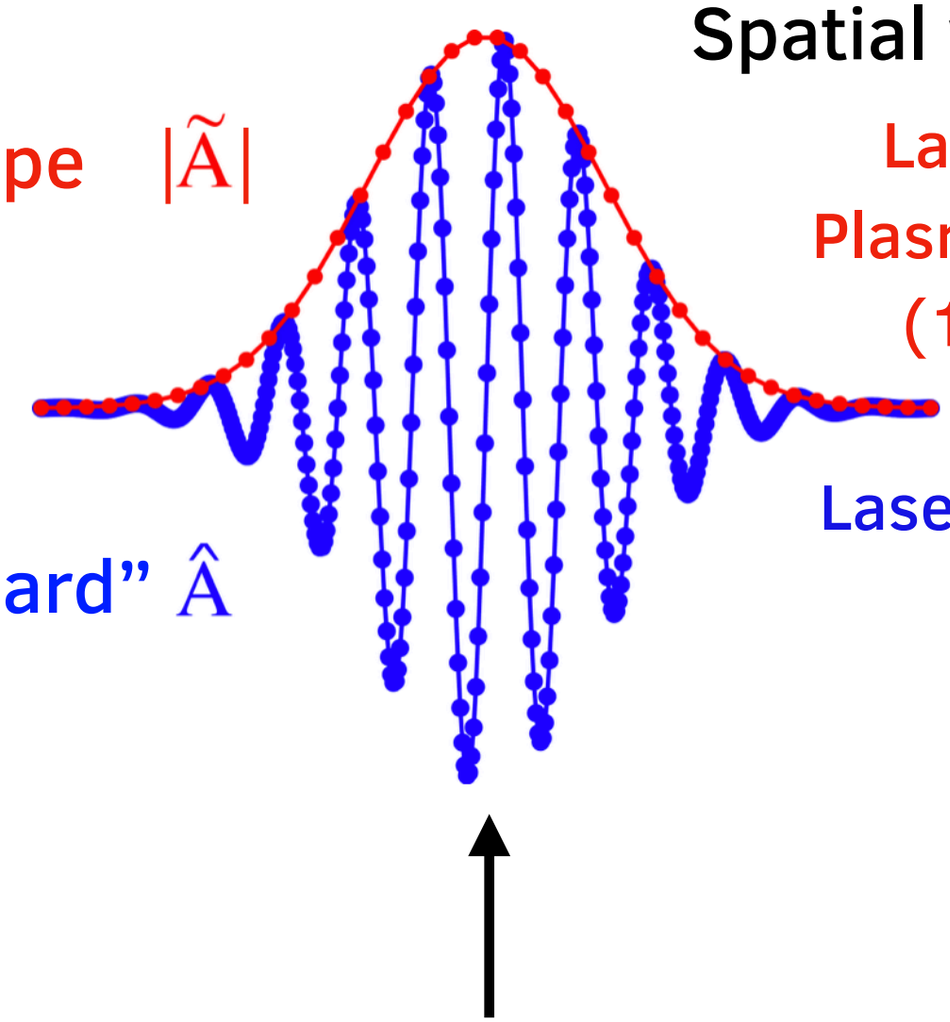




Laser Envelopes need less sampling points

Laser Envelope $|\tilde{A}|$

Laser "Standard" $\hat{A}$



Spatial variation scales:

Laser length ~
Plasma wavelength
(10-100 μm)

Laser wavelength
(~1 μm)

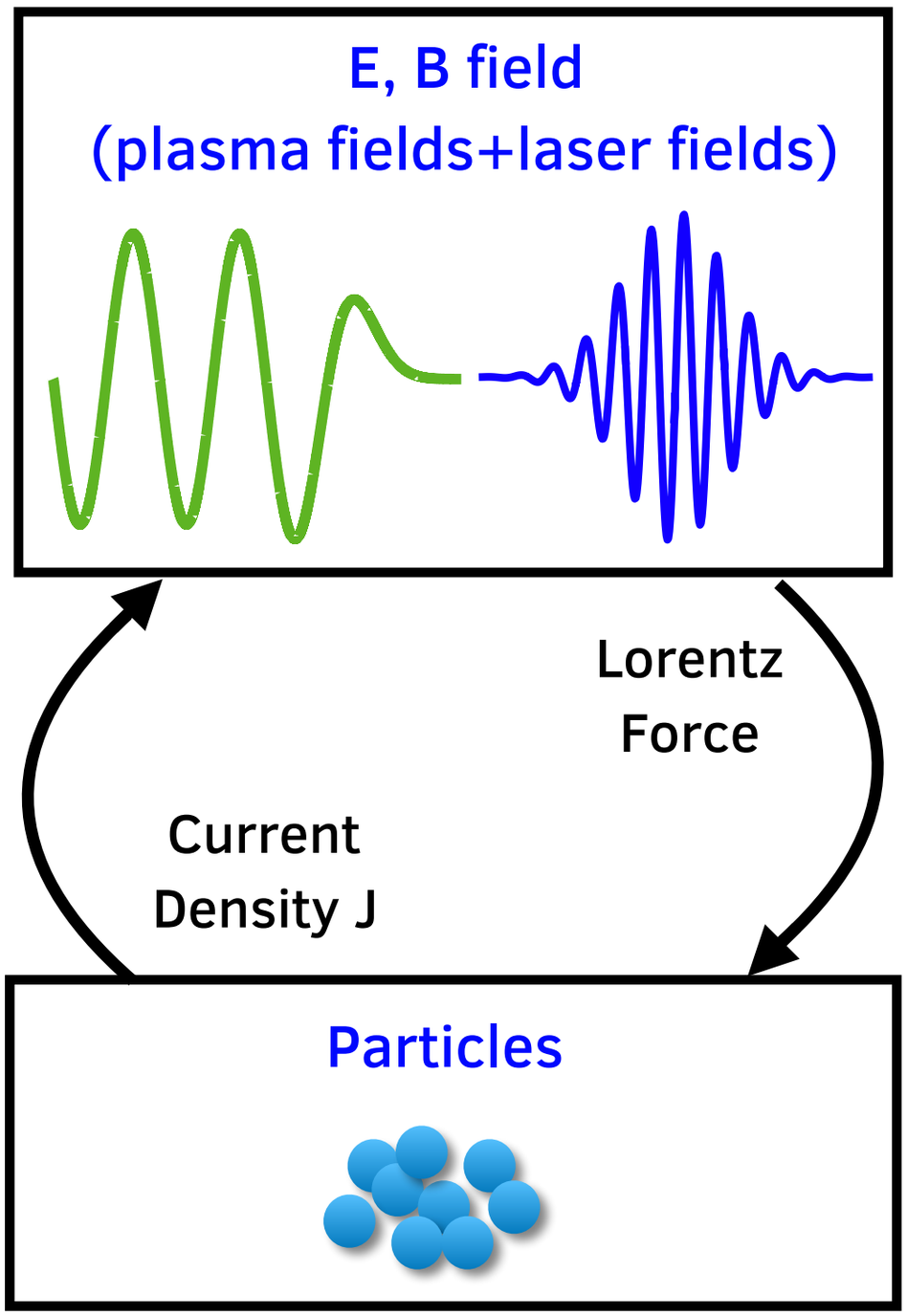
D. Terzani and P. Londrillo,
submitted (2019)

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

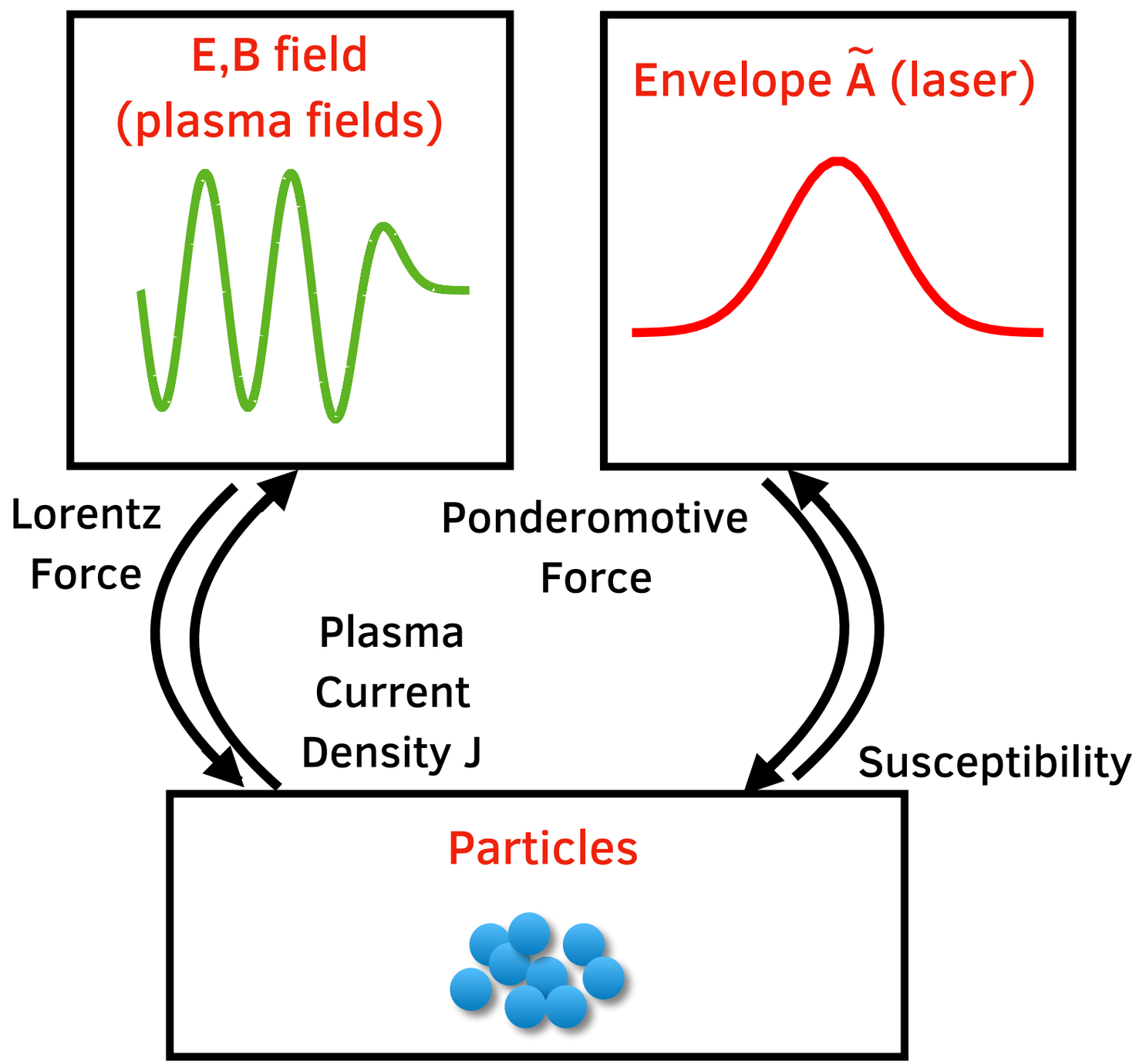
⟶ Larger Δx and Δt can be used!

Structure of a PIC code with Laser Envelope

Standard PIC



Envelope (/Ponderomotive) PIC

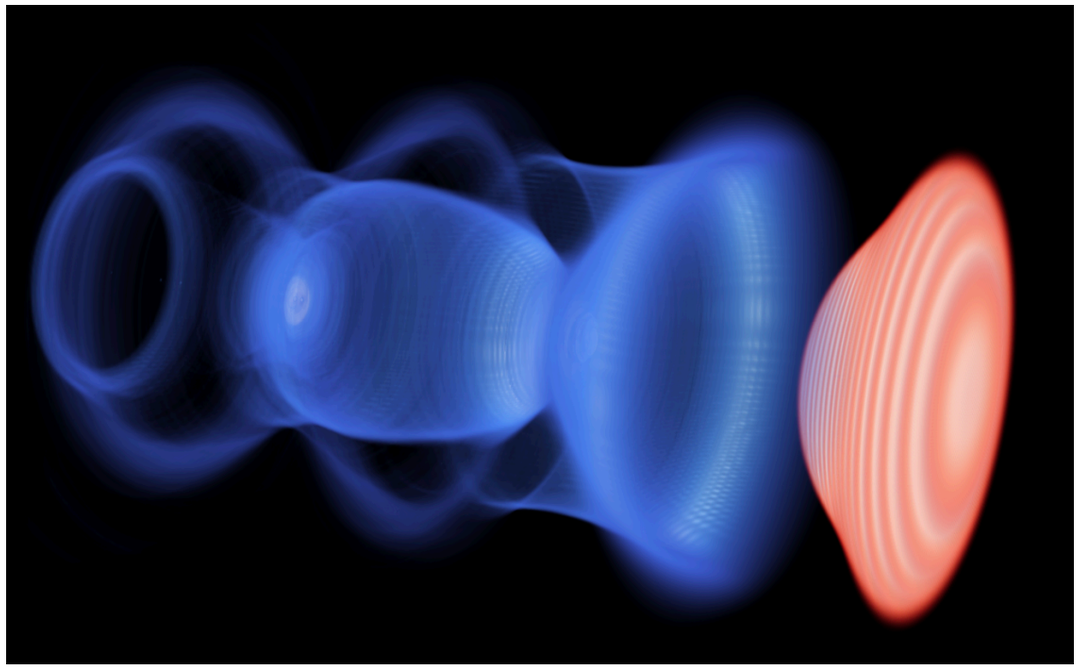


A collaborative open source Particle in Cell code

Smilei)

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

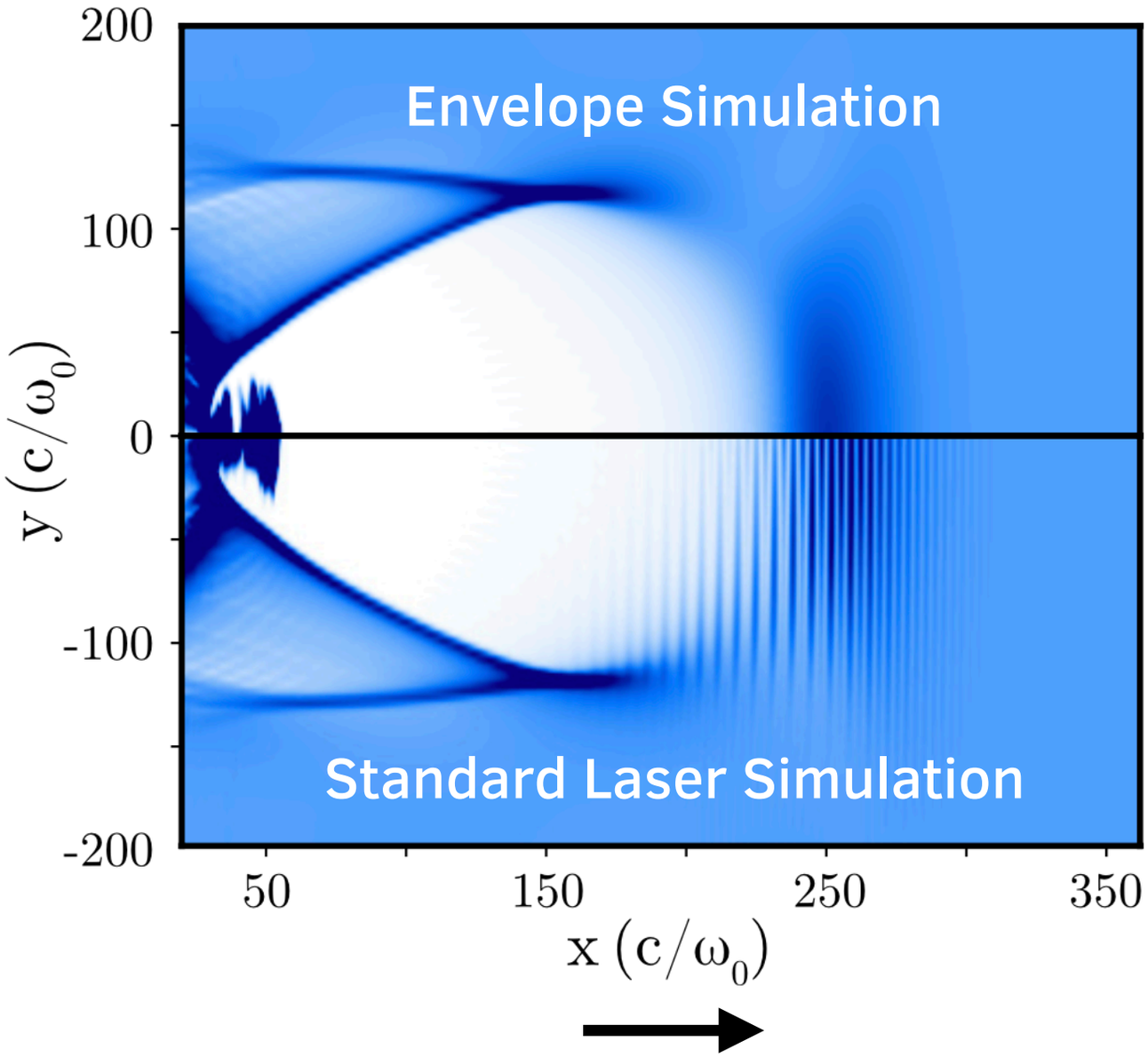
- 1D, 2D, 3D, Quasi-3D Geometry
- Hybrid MPI-OpenMP
- Python Input/Output Interface
- Advanced Dynamic Load Balancing
- Dynamic Adaptive Vectorisation
- Ionisation, Collisions, QED effects
- Envelope Model for the Laser
- Relativistic Beam Field Initialisation

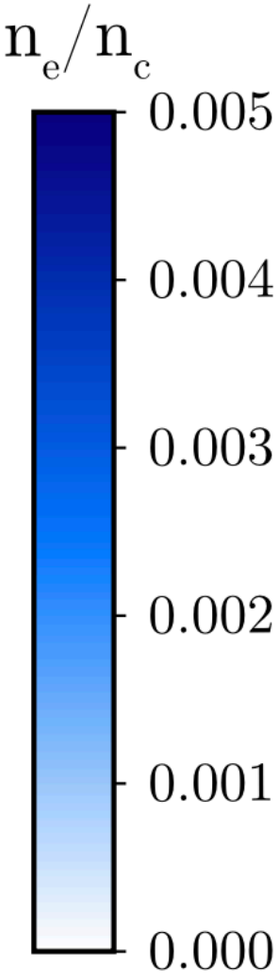


J. Derouillat, et al., Comput. Phys. Commun. 222, 351-373 (2018)

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

Standard Laser simulation

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

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

Envelope simulation

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

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

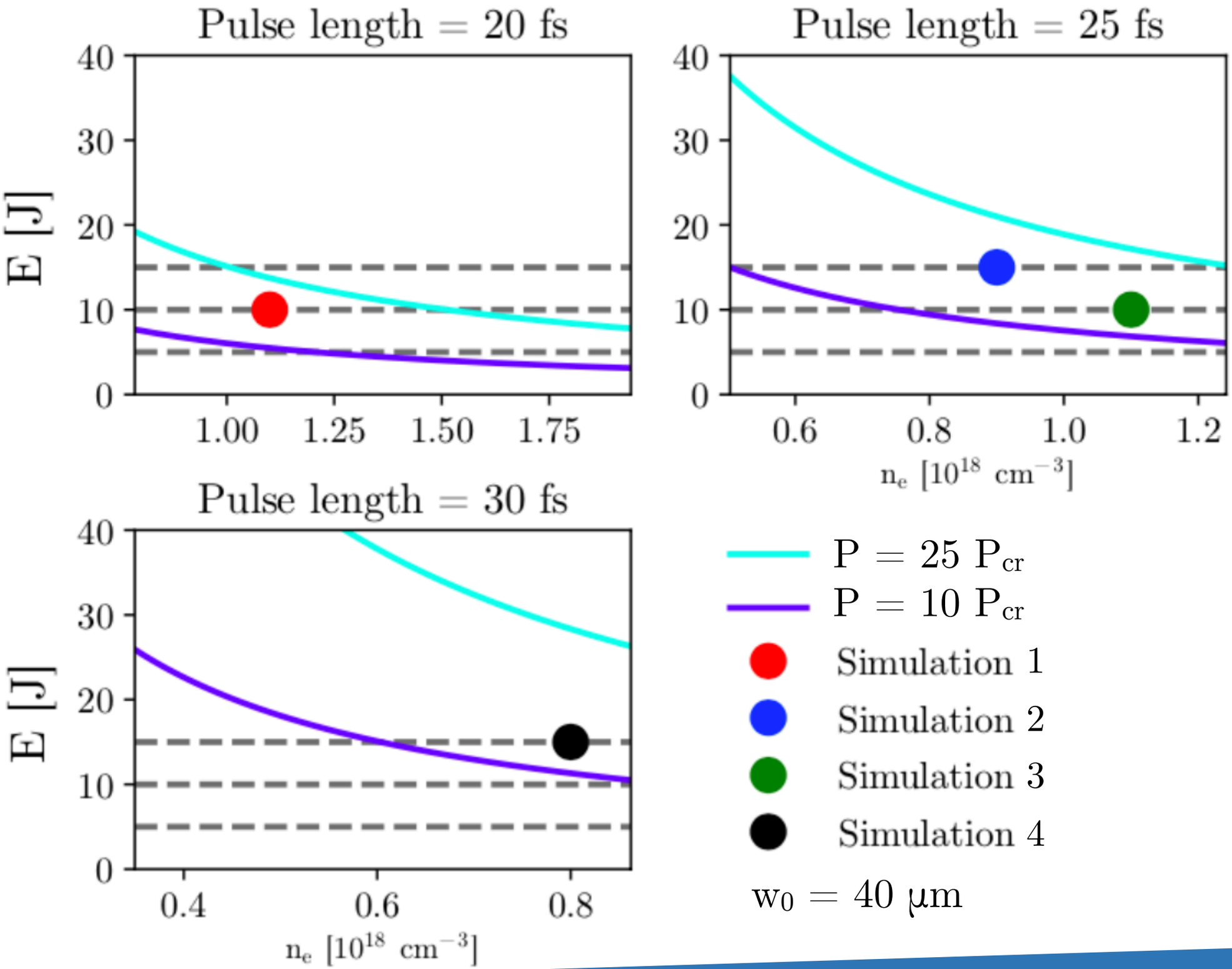
$$\frac{T_{\text{Standard Laser}}}{T_{\text{Envelope}}} = 20$$

@1 mm

$T_{Envelope}$= 16 kh-cpu

1st stage: possible working points

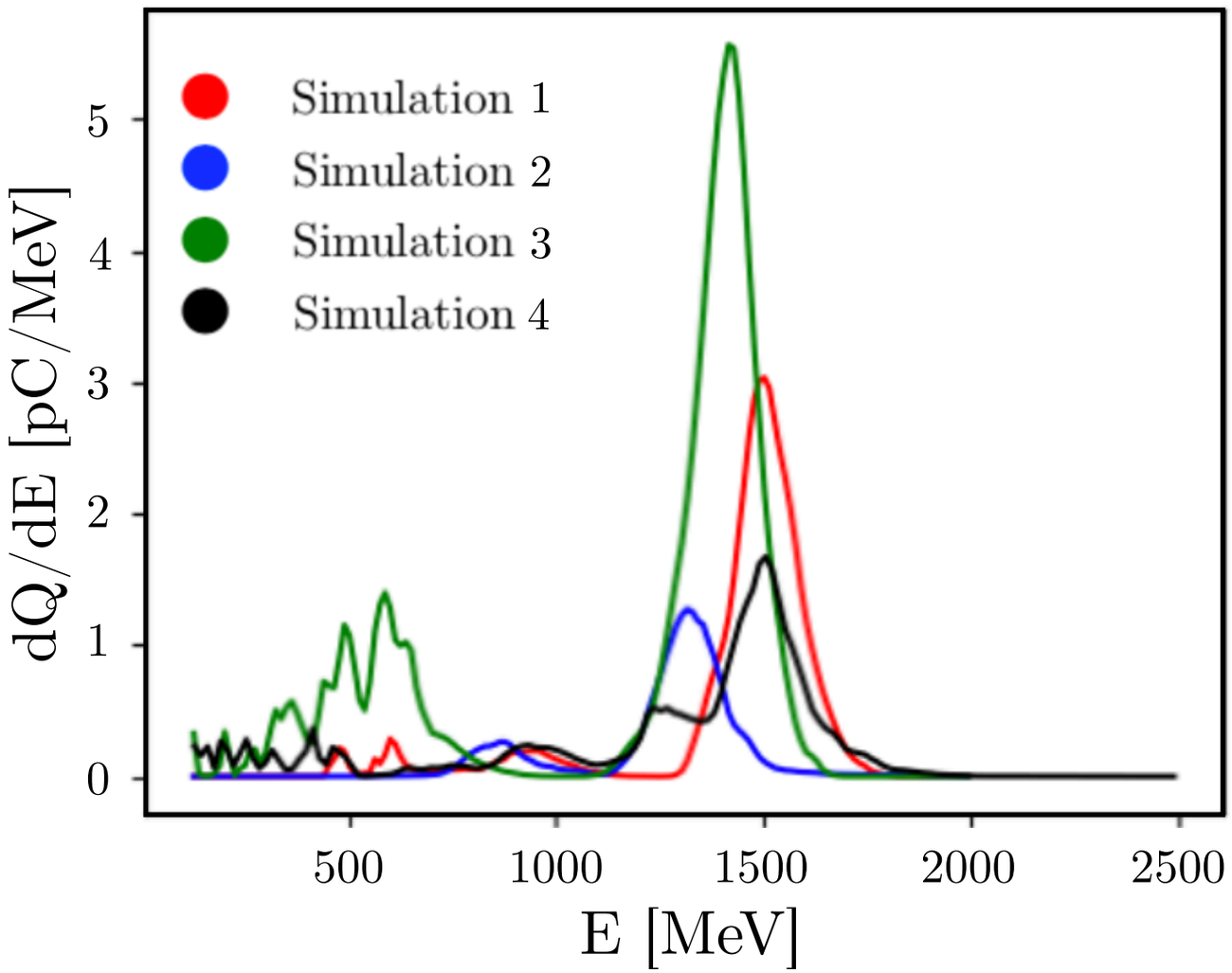
Scalings from A. Beck et al. , NIM A 740 (2014)



1st stage: working points

@12 mm of propagation, Preliminary Results

Simulation	1	2	3	4
E_{Laser} [J]	10	15	10	15
a_0	2.95	2.65	3.25	2.95
$L_{FWHM,\ Laser}$ [fs]	20	25	25	30
Q [pC]	535	229	949	317
E_{peak}[GeV]	1.5	1.3	1.4	1.5
ΔE/E (%)	10.8	14.3	11.5	11.6
$E_{e\ beam}$ [J]	0.8	0.3	1.3	0.5
$E_{e\ beam}/E_{Laser}$	8 %	3 %	9 %	3 %



Case Study: Multistage LWFA experiments

Gas jet, ~ mm

CileX Apollon

1st Plasma Stage

1st Laser Pulse

Injected Electrons

~ 50-200 MeV

Magnetic Beam Transport

Case study

2nd Plasma Stage

2nd Laser Pulse

Laser

plasma channel, ~ 10 cm

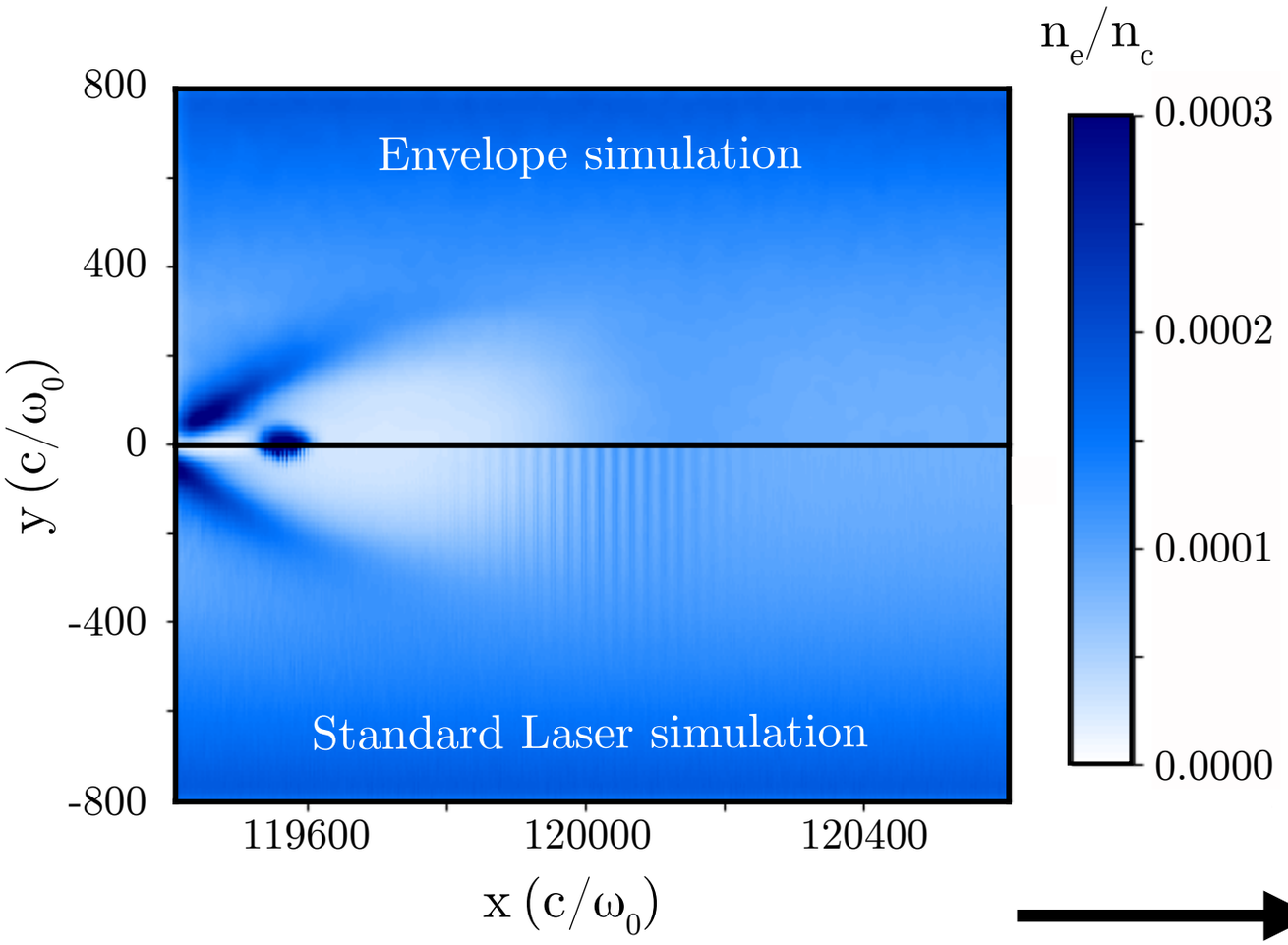
Accelerated Electrons

~ 10 GeV

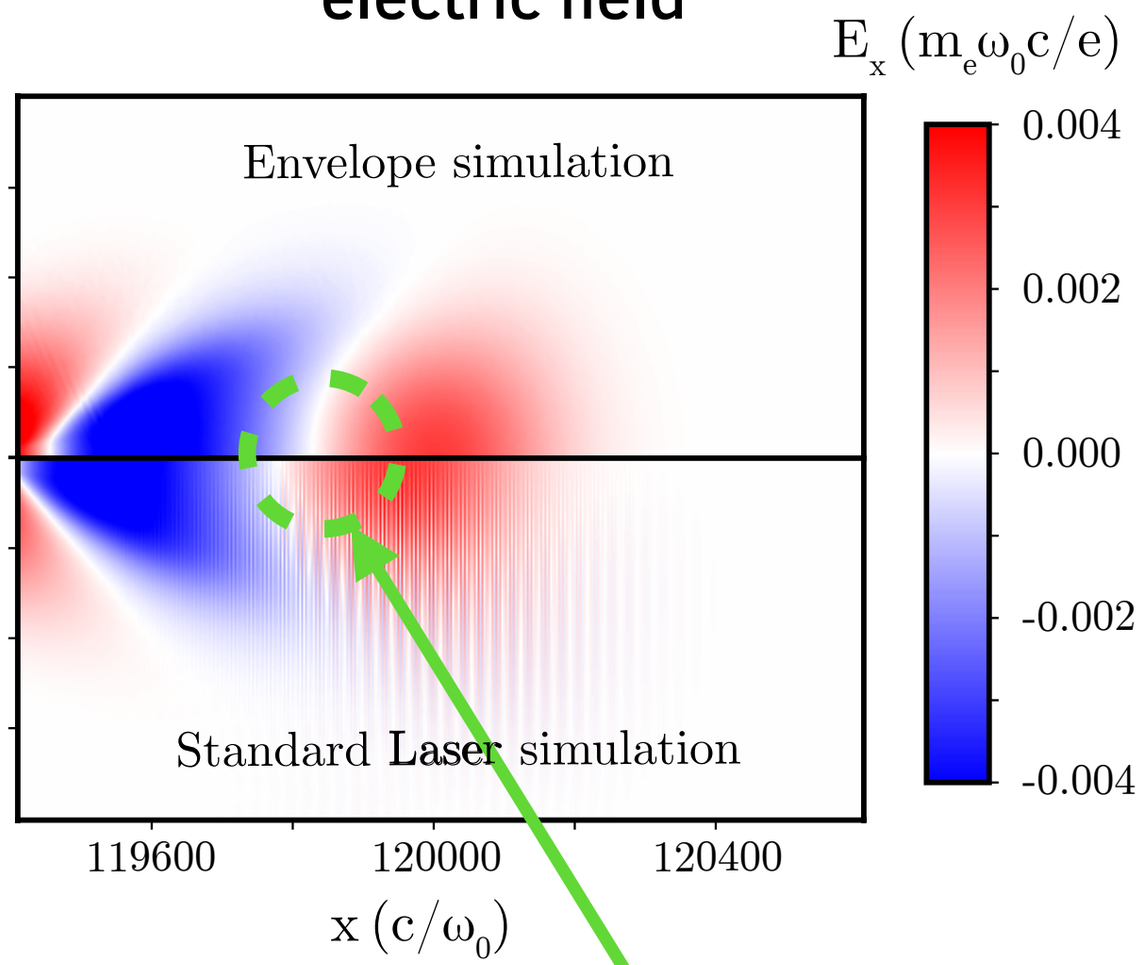
Simulation of External injection LWFA

Comparison @15 mm of propagation, Preliminary Results

Electron density



Longitudinal electric field



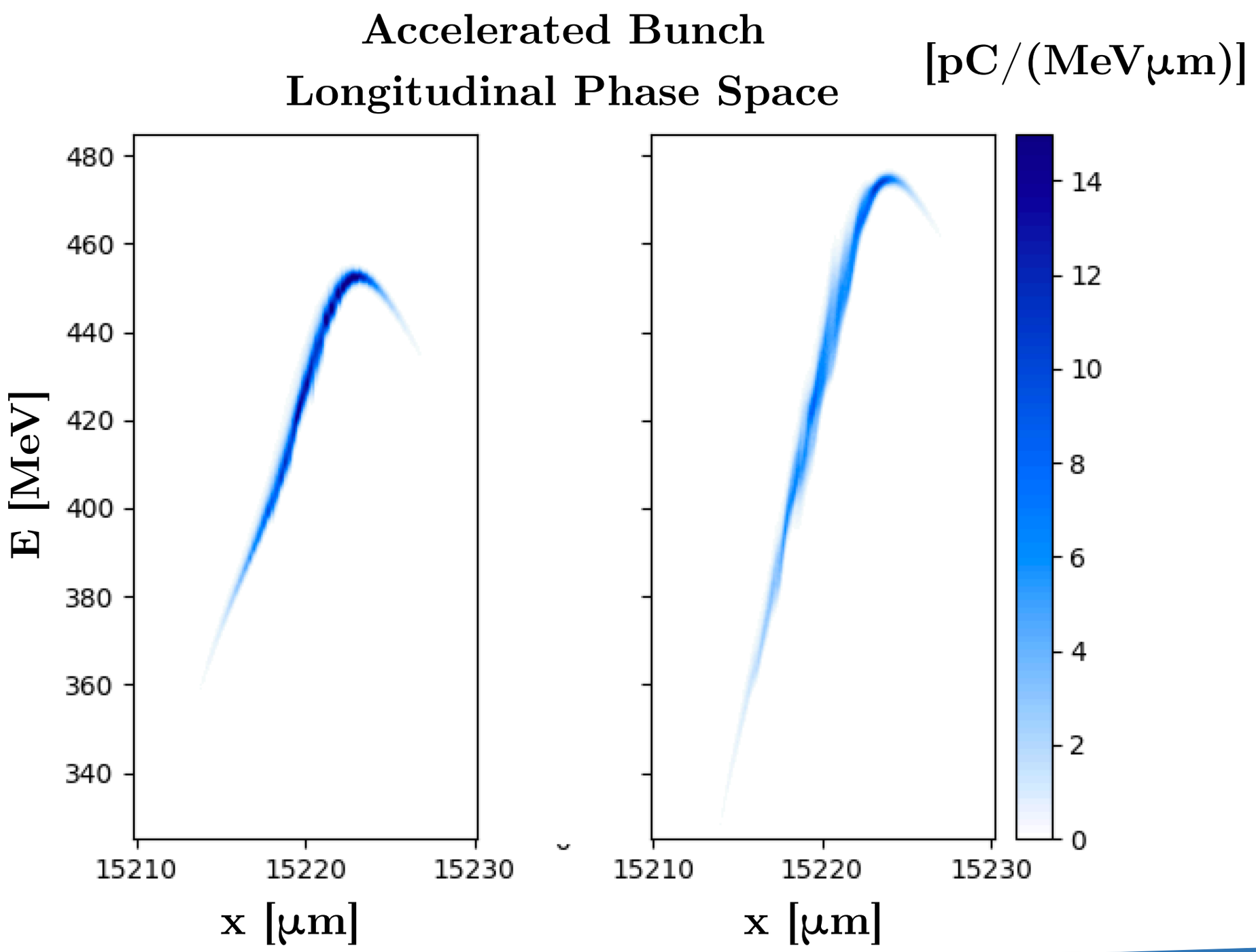
Propagation Direction

Envelope PIC less dispersive than standard PIC

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

Simulation of External injection LWFA

Comparison @15 mm of propagation, Preliminary Results



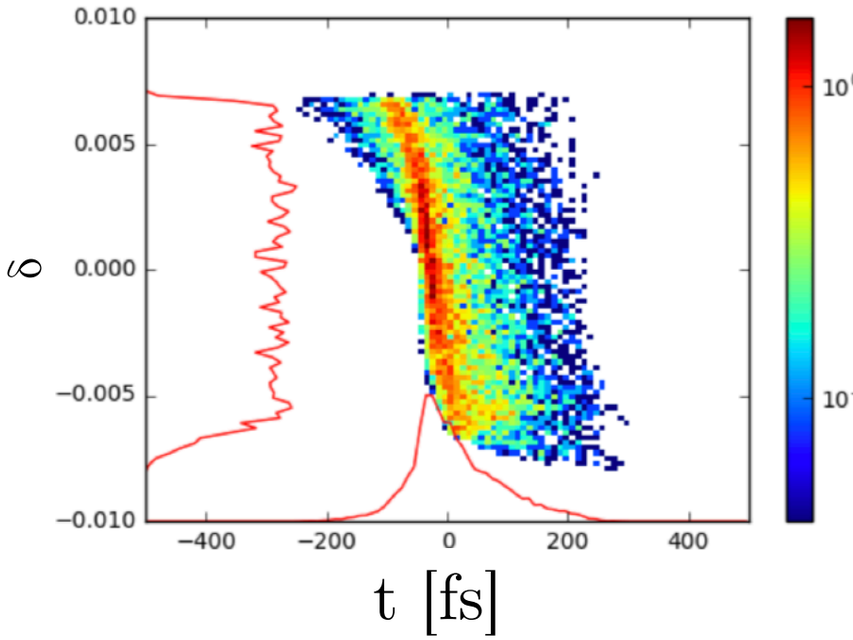
Simulation of External injection LWFA

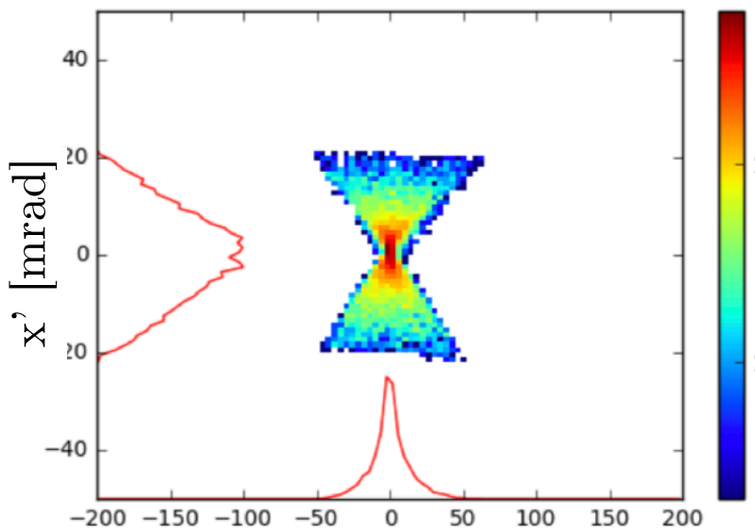
Comparison @15 mm of propagation, Preliminary Results

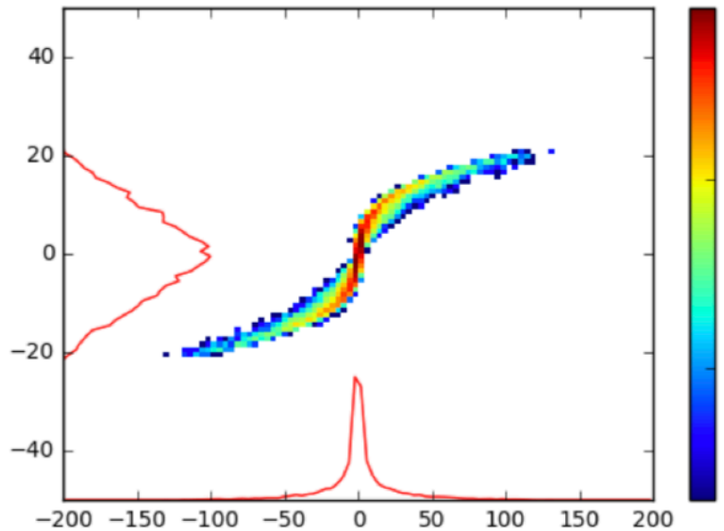
Laser		Beam Params	Initial Value	Standard PIC	Envelope PIC
w_0 [μm]	45	Q [pC]	30	29.98	29.96
τ_{FWHM} [fs]	107	$\sigma_x, \sigma_y, \sigma_z$ [μm]	2.0, 1.3, 1.3	2.0,1.5,1.4	2.0,1.9, 2.1
a_0	1.4	$\varepsilon_{n,y}, \varepsilon_{n,z}$ [mm-mrad]	1.0, 1.0	2.0, 2.1	4.3, 5.7
Plasma		E [MeV]	150	427	432
n_0 [10^{17} cm^{-3}]	1.5	ΔE/E [%]	0.5	4.7	6.8

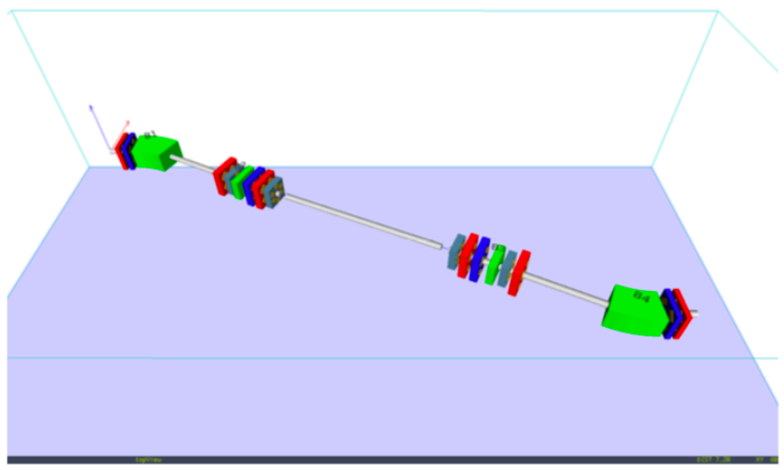
Next step: simulations with realistic electron beam

Beam after transport from 1st stage (transport by Antoine Chance):





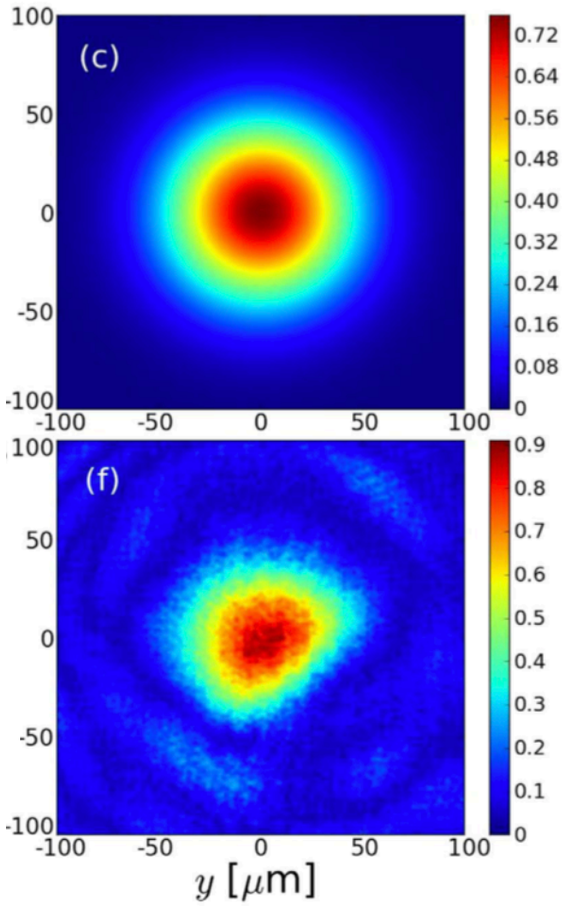




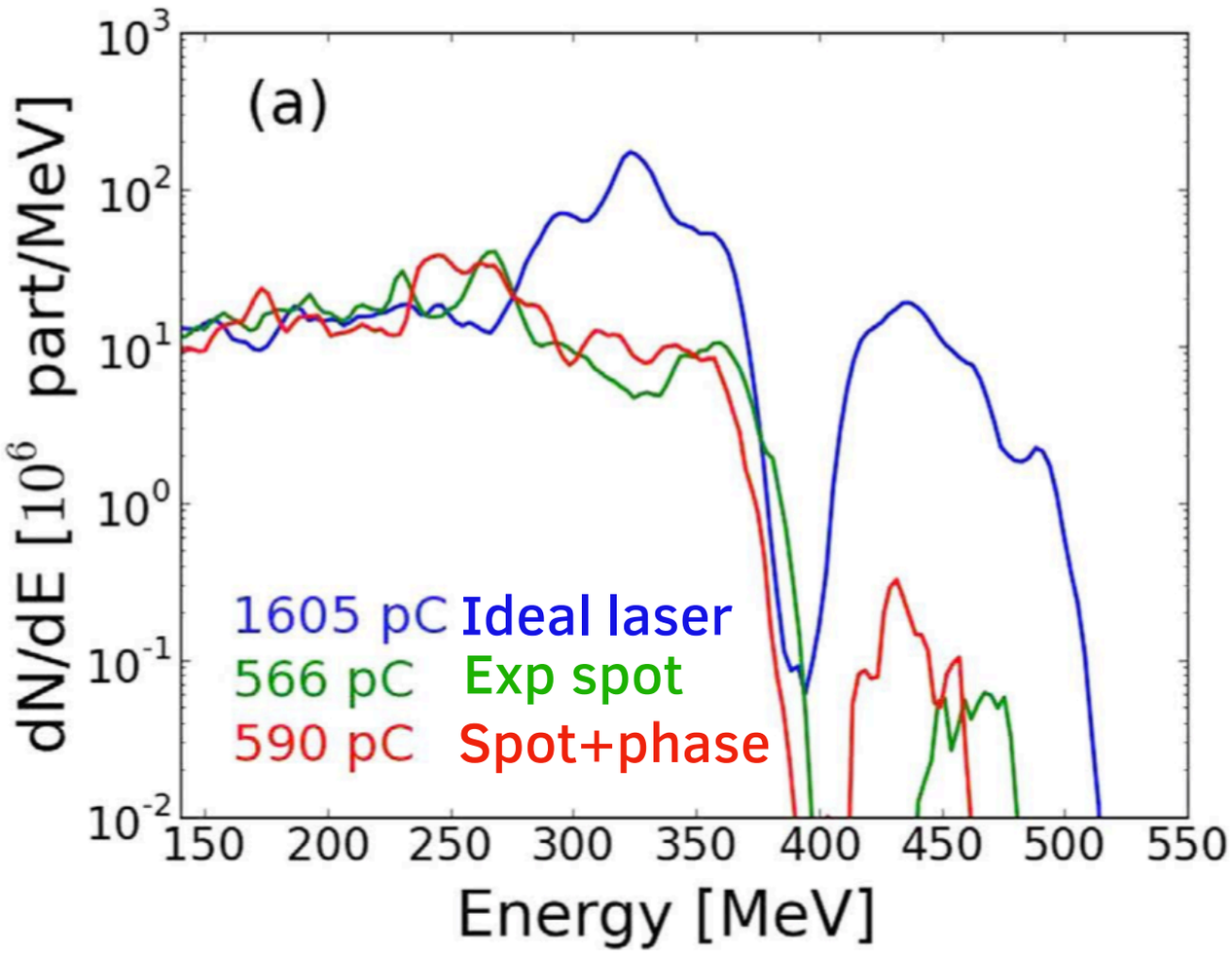
Next step: realistic laser simulations

Ideal
Laser profile

Realistic
Laser profile



LWFA electron spectrum:



J. Ferri et al., Scientific Reports 6, 27846 (2016)

B. Beaurepaire et al., Phys. Rev X 5, 031012 (2015)

Conclusions and perspectives

- Quick envelope model implemented for 3D LWFA PIC simulations
- Model benchmarked in nonlinear regimes and 15mm external injection
- Possible CILEX first stage working points found through parametric scan
- Model suited for multi-stage LWFA simulation
- Future development: envelope model + cylindrical symmetry
- Next steps: simulations with realistic laser beams, realistic particle beams

Acknowledgements

Group GALOP

- Arnaud Beck, Imen Zemzemi, M. Khojoyan, A. Specka

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

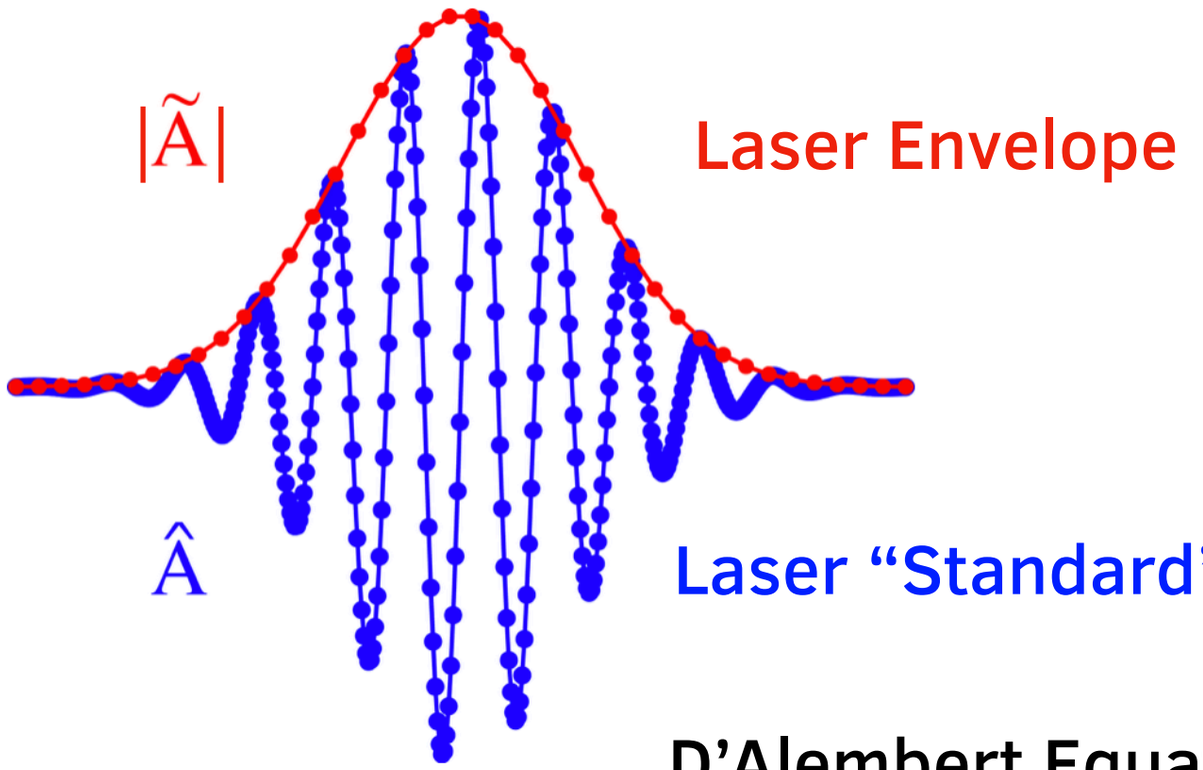
This work used computational resources of TGCC, CINES, through the allocation of resources 2018-A0010510062 granted by GENCI (Grand Equipement National de Calcul Intensif) and Grand Challenge "Irene" 2018 project gch0313 made by GENCI.

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, submitted (2018)



Hypothesis:

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

Laser Complex Envelope

+

D’Alembert Equation:

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

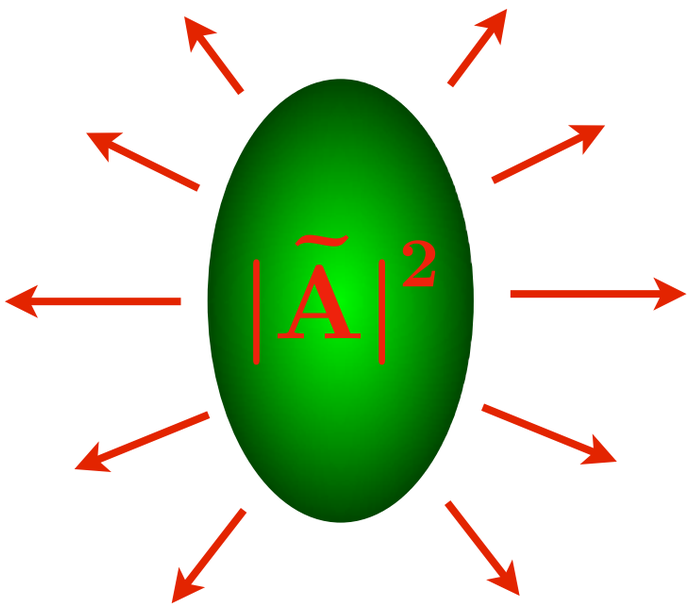
=

Envelope Equation:

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

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)