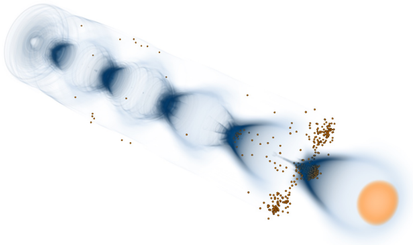
Spectral phase control for optimized ionization injection in laser wakefield acceleration

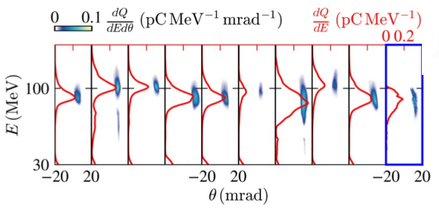
F. Massimo, I. Moulanier, M. Backhouse, L. T. Dickson, T. L. Steyn, B. Cros

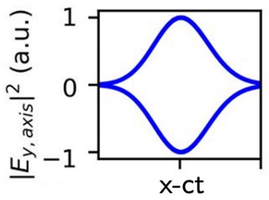
21/09/2026

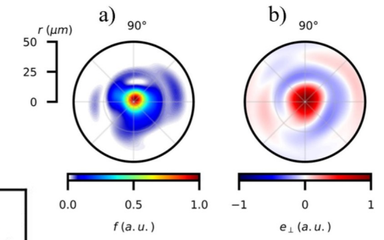
Plan



- Spectral phase optimization experiment @ Lund Laser Centre (LLC)
- Realistic modeling of laser Asymmetric Chirped laser pulses
  - Transverse laser description
  - Temporal laser description
- Modeling results for LLC experiment
- Conclusions



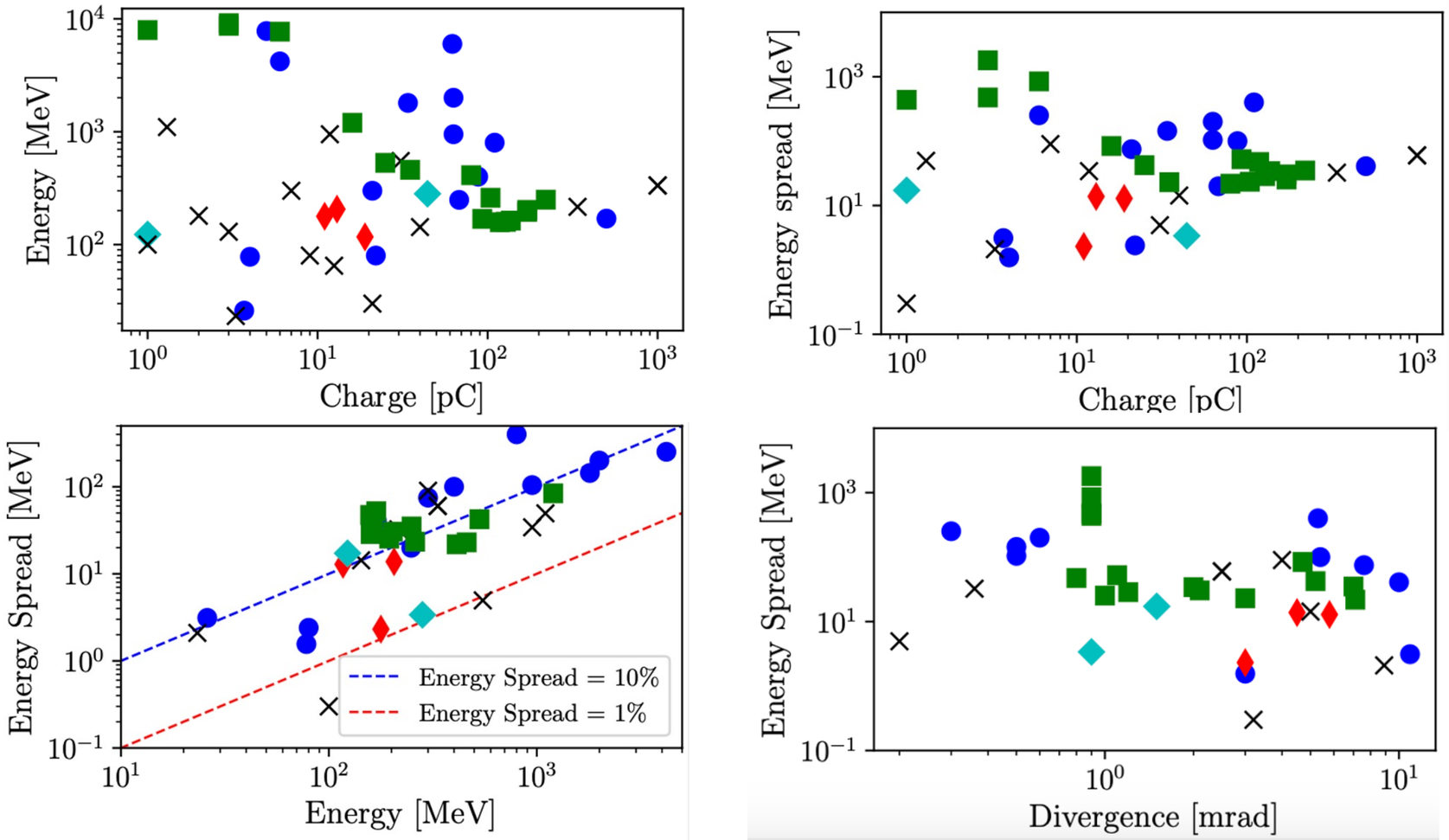




Caveat:
For more details on the experiment and on Bayesian Optimization
See M. Backhouse's talk at 7th EAAC (2025)
https://agenda.infn.it/event/46259/contributions/270104/

Laser Wakefield Acceleration (LWFA): a challenging e-beam optimization problem

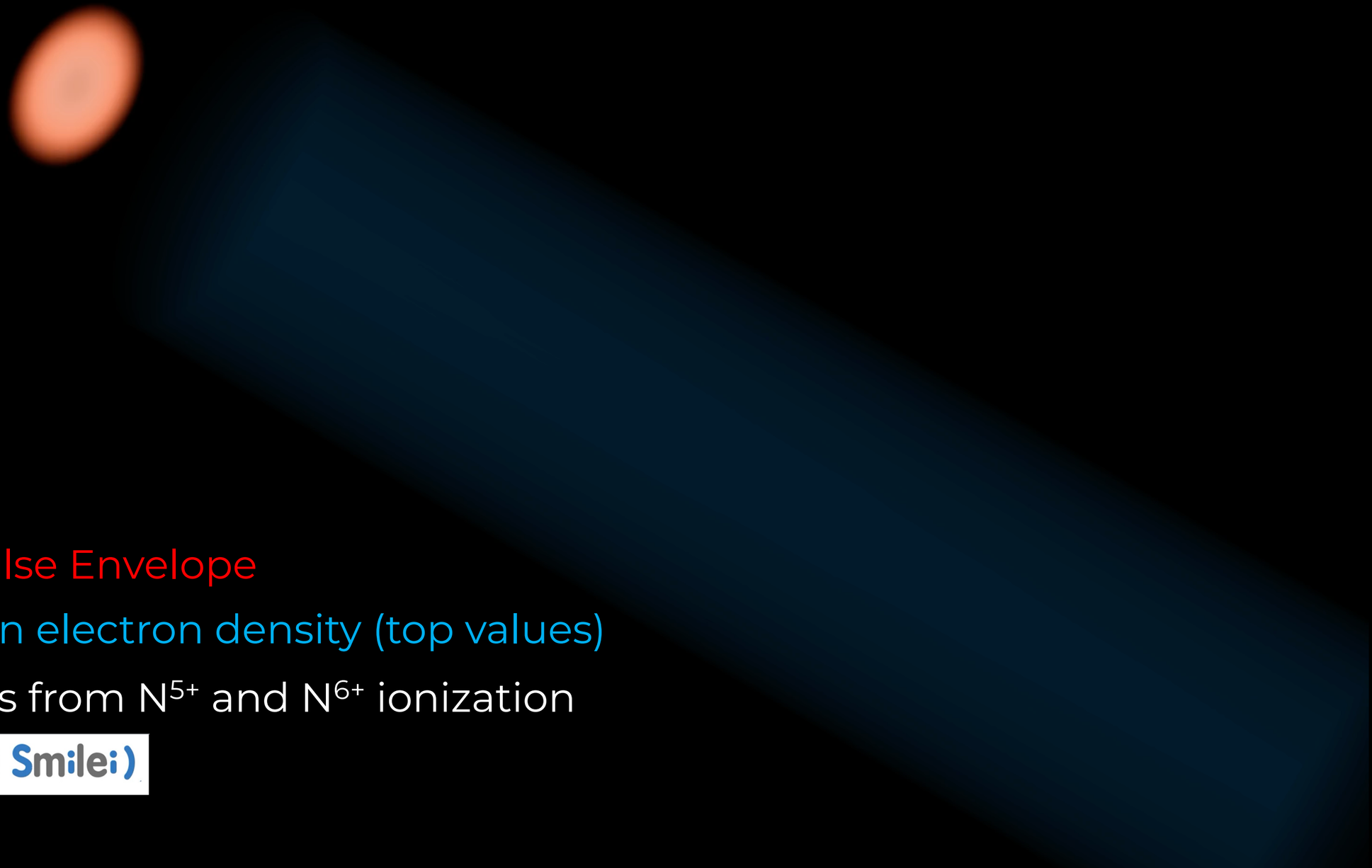
Self-Injection **Ionization Injection** **Tailored-density injection** **Ionization+Tailored-density injection**



Caveat:
List far from complete,
Last point from 2025

F. Massimo,
Mémoire HDR (2025)

In this talk: LWFA with ionization injection



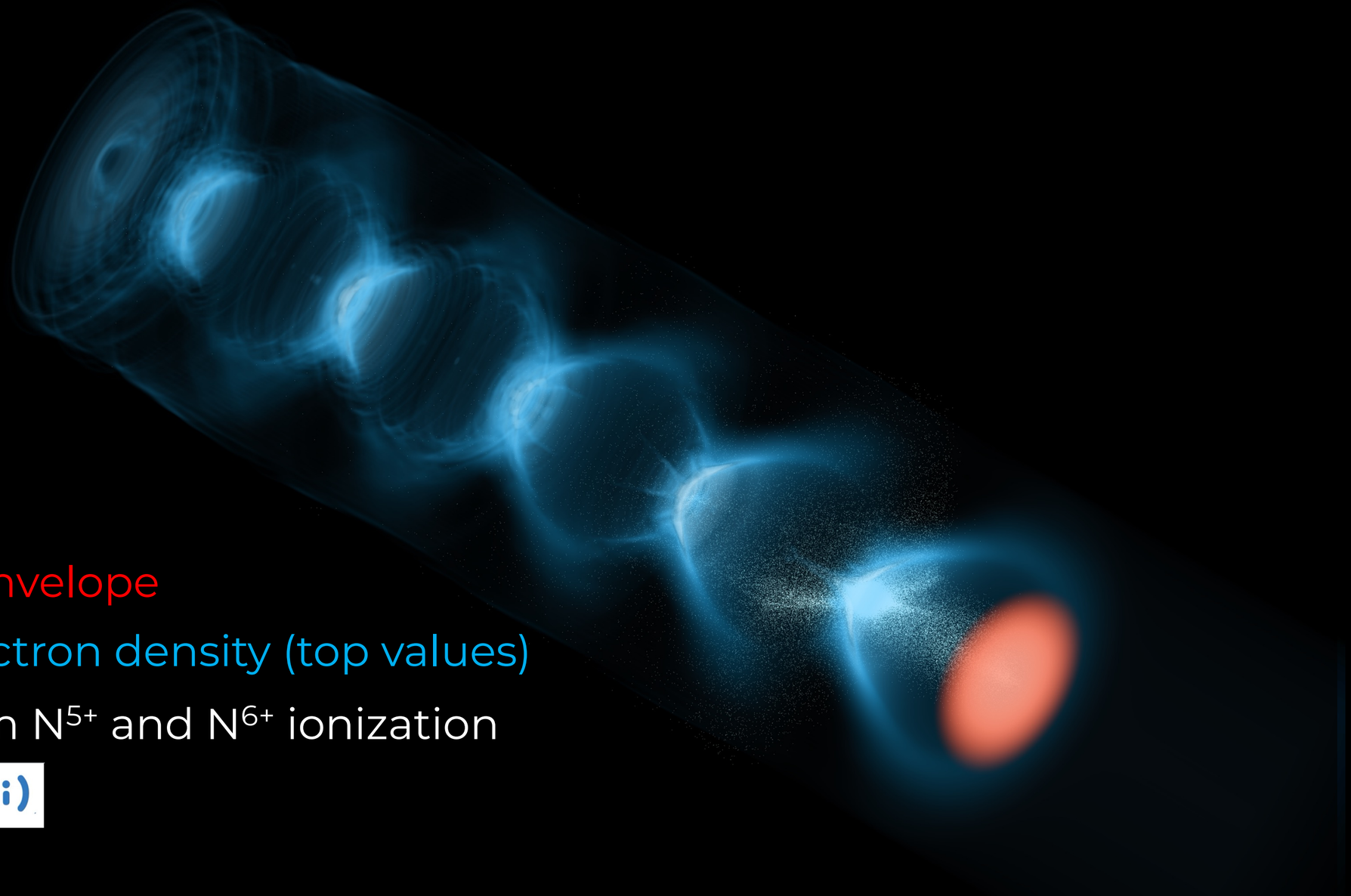
Laser Pulse Envelope

Hydrogen electron density (top values)

Electrons from N^{5+} and N^{6+} ionization

Lpgp cnrs Smilei

In this talk: LWFA with ionization injection



Laser Pulse Envelope

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Lpgp cnrs Smilei

Spectral phase definition

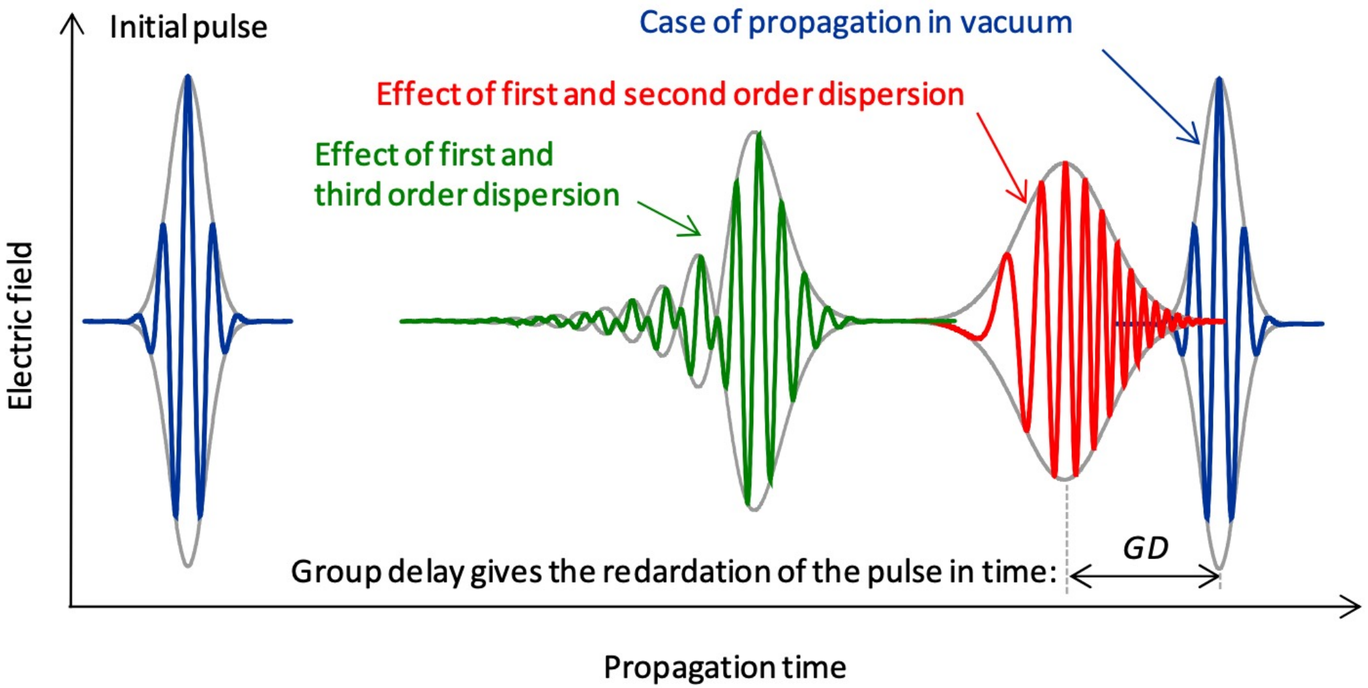
Spectral Phase

$$\mathcal{F}\{E(t)\} = E(\omega) = |E(\omega)| \exp[i\Phi(\omega)]$$

The chirp terms Φ_n in this series can be controlled with a DAZZLER

$$\phi_c(\omega) = \sum_{n=0}^{+\infty} \phi_n \frac{(\omega - \omega_0)^n}{n!}$$

A. Borzsonyi et al., Appl. Sci. 2013



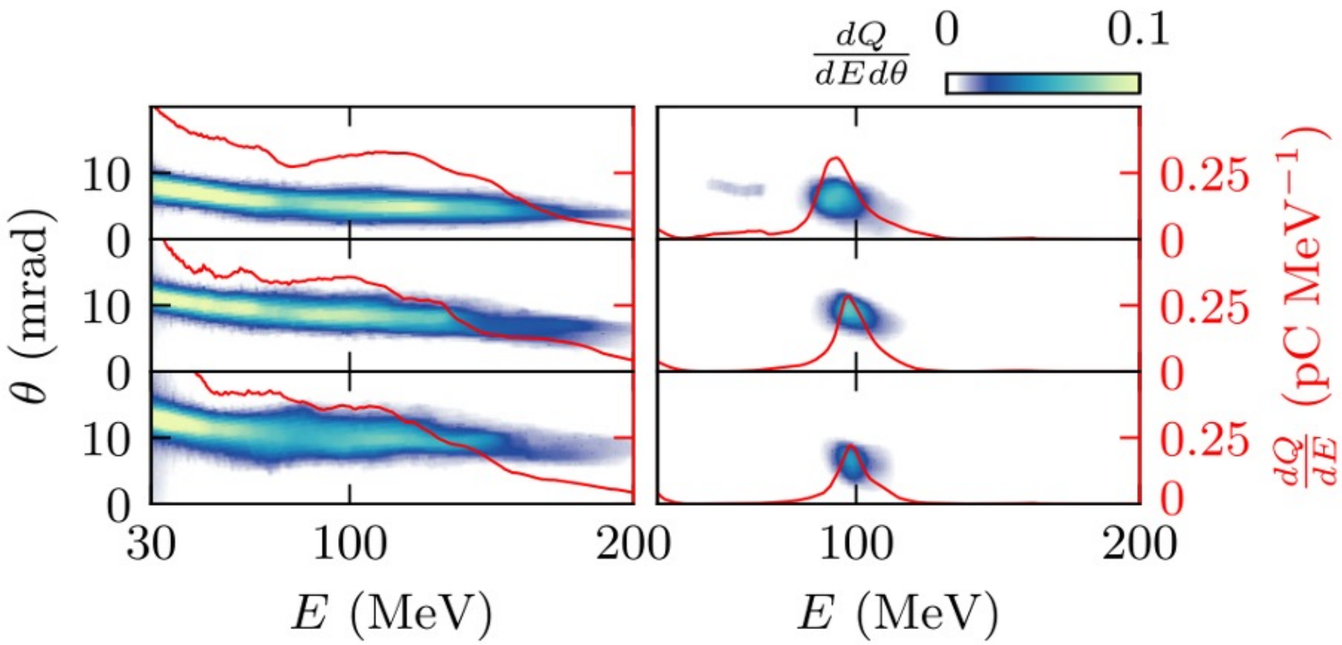
Bayesian Optimizations of e-beam quality from LWFA with tuning of the spectral phase terms of the laser:

- R. J. Shalloo et al., Nat, Comm. 2020
- M. Backhouse et al., PRAB 2025
- B. Z. Djordjević et al., PoP 2026
- F. M. Herrmann et al., Mach. Learn.: Sci. Technol. 2026

Spectral phase optimization experiment @ Lund Laser Centre

E- spectra without Spectral phase optimization

E- spectra with Spectral phase optimization



e- beam spectra are asymmetric
→ Need for **transverse** laser reconstruction (e.g. Gerchberg-Saxton Algorithm)

The beam quality depends on the spectral phase → Need for **temporal** laser reconstruction

How do we couple the two descriptions?

M. Backhouse et al., Phys. Rev. Accel. Beams 2025

See M. Backhouse's talk at 7th EAAC https://agenda.infn.it/event/46259/contributions/270104/

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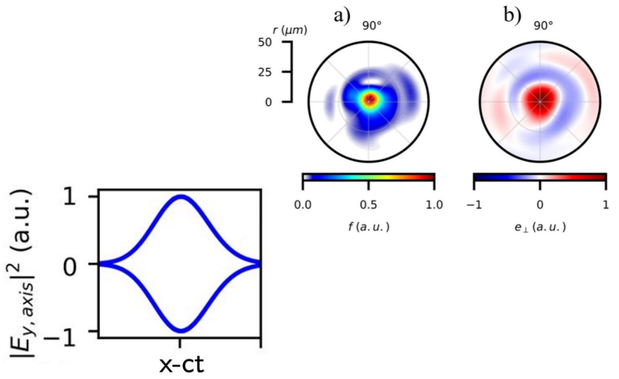


Particle in Cell (PIC) simulations and laser initalization

Laser field initialization

PIC time loop

Field Interpolation

$$[\mathbf{E}, \mathbf{B}] \rightarrow [\mathbf{E}_p, \mathbf{B}_p]$$

Maxwell Solver

$$\partial_t \mathbf{E} = -\mathbf{J} + \nabla \times \mathbf{B}$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

Δt

Particle Pusher

$$d_t \mathbf{p}_p = q_s \left(\mathbf{E}_p + \mathbf{v} \times \mathbf{B}_p\right)$$

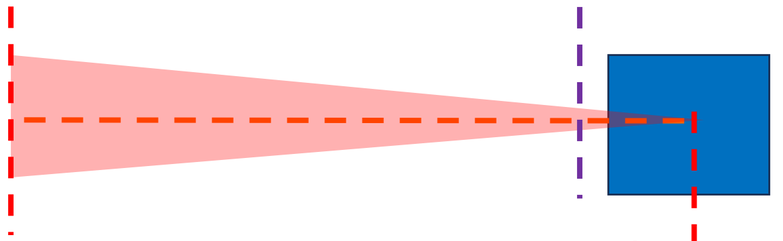
$$d_t \mathbf{x}_p = \mathbf{p}_p / \left(m_s \gamma\right)$$

Current Projection

$$[\mathbf{x}_p, \mathbf{p}_p] \rightarrow [\rho_s, \mathbf{J}_s]$$

5th Smilei User and Training Workshop,
https://indico.math.cnrs.fr/event/13081/

PIC simulations normally start here



Gas target for LWFA (~mm)

Laser vacuum focal plane (Note: the plasma modifies the propagation)

For PIC simulation initialization, we need to know the laser field distribution in vacuum in space and time

Lasers in this presentation: separated Transverse and Temporal part (see J. R. Pierce et al., PRX 2023)

Diffraction

Envelope equation
in comoving coordinates
ξ=x-ct, s=x

$$\nabla_\perp^2 \tilde{\mathcal{E}} + 2ik_0 \frac{\partial \tilde{\mathcal{E}}}{\partial s} + 2\frac{\partial^2 \tilde{\mathcal{E}}}{\partial \xi \partial s} + \frac{\partial^2 \tilde{\mathcal{E}}}{\partial s^2} = 0$$

Lasers in this presentation: separated Transverse and Temporal part (see J. R. Pierce et al., PRX 2023)

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No Spatio-temporal Couplings

For most pulses for LWFA,
OK if $s\text{-}s_{focus} < L_{STC} \sim 2\pi\ (c\tau_0/\lambda_0) Z_R$
i.e. within many Rayleigh lengths Z_R
from focus if pulse length $c\tau_0 >> \lambda_0$

Separable envelope

Temporal envelope (including spectral phase effects)

$$E(x,y,z,t) = \mathrm{Re}\left[\tilde{E}(x, y-y_0, z-z_0, t)\, T(x-ct)\, e^{ik_0(x-ct)}\right]$$

Transverse envelope

Lasers in this presentation: separated Transverse and Temporal part (see J. R. Pierce et al., PRX 2023)

Slow envelope variations

Diffraction

Paraxial wave equation

Envelope equation in comoving coordinates

ξ=x-ct, s=x

$$\nabla_\perp^2 \tilde{\mathcal{E}} + 2ik_0 \frac{\partial \tilde{\mathcal{E}}}{\partial s} + 2\frac{\partial^2 \tilde{\mathcal{E}}}{\partial \xi \partial s} + \frac{\partial^2 \tilde{\mathcal{E}}}{\partial s^2} = 0 \longrightarrow \nabla_\perp^2 \tilde{E} + 2ik_0 \frac{\partial \tilde{E}}{\partial x} = 0$$

No Spatio-temporal Couplings

For most pulses for LWFA,

OK if $s\text{-}s_{focus} < L_{STC} \sim 2\pi\,(c\tau_0/\lambda_0)Z_R$

i.e. within many Rayleigh lengths Z_R from focus if pulse length $c\tau_0 >> \lambda_0$

Temporal envelope (including spectral phase effects)

Separable envelope

$$E(x,y,z,t) = \mathrm{Re}\left[\tilde{E}(x, y-y_0, z-z_0, t)\, T(x-ct)\, e^{ik_0(x-ct)}\right]$$

Transverse envelope:
Paraxial wave equation solution, e.g. Gaussian beam, LG beams, Flattened Gaussian Beams, etc

Asymmetric Chirped Electric field reconstruction (ACE)

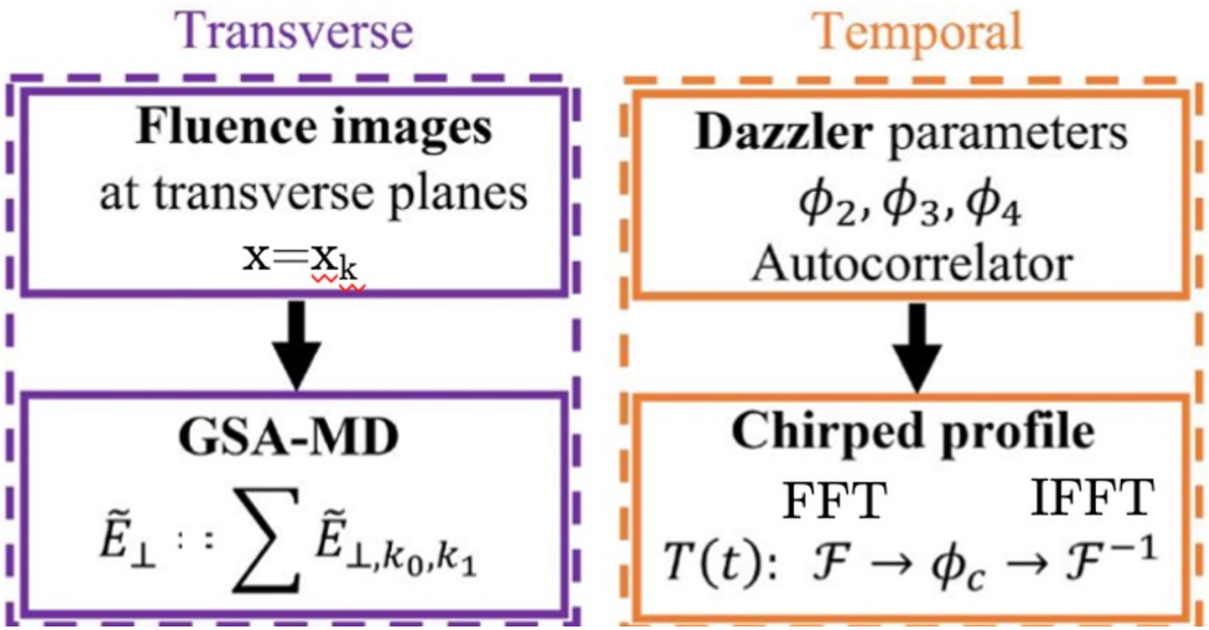
Inputs from experiment

I. Moulanier et al., PoP 2026

Asymmetric Chirped Electric field reconstruction (ACE)

Inputs from experiment

Reconstruction



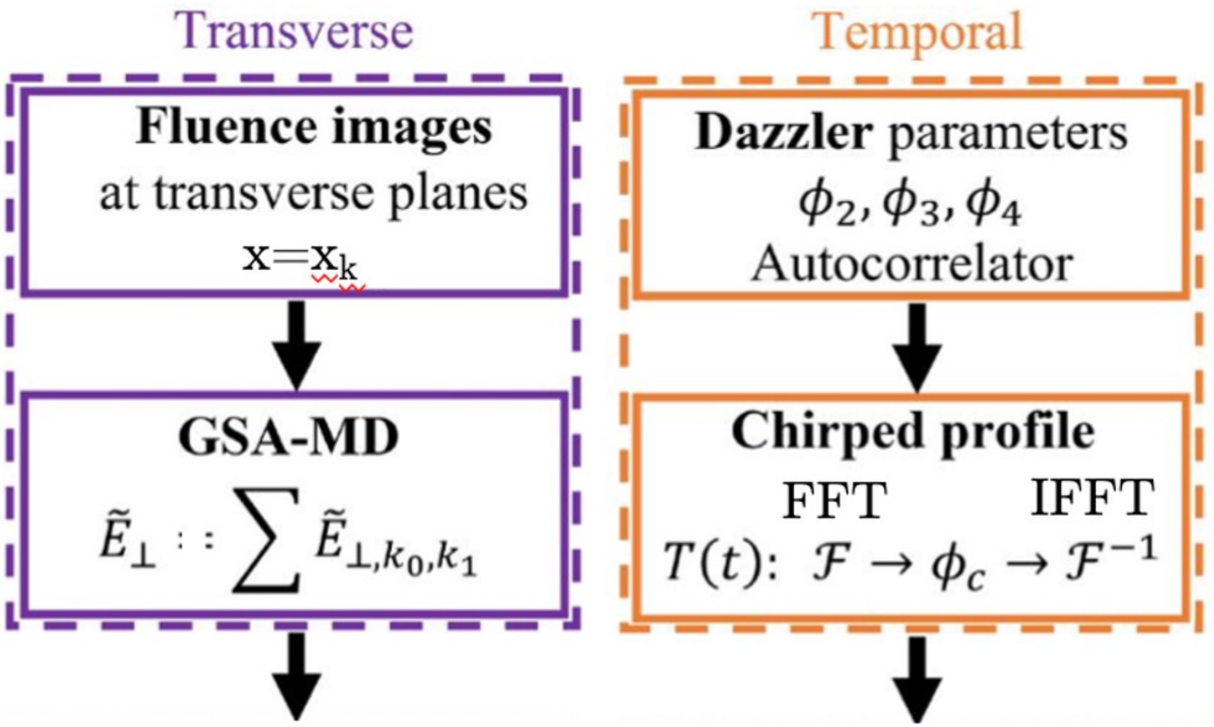
I. Moulanier et al., PoP 2026

Asymmetric Chirped Electric field reconstruction (ACE)

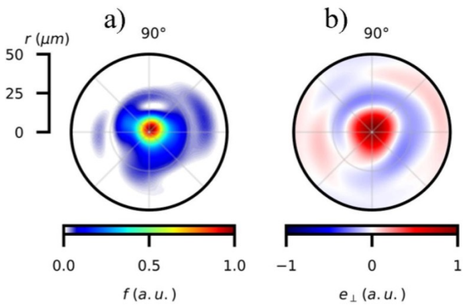
Inputs from experiment

Reconstruction

Laser electric field for PIC simulation



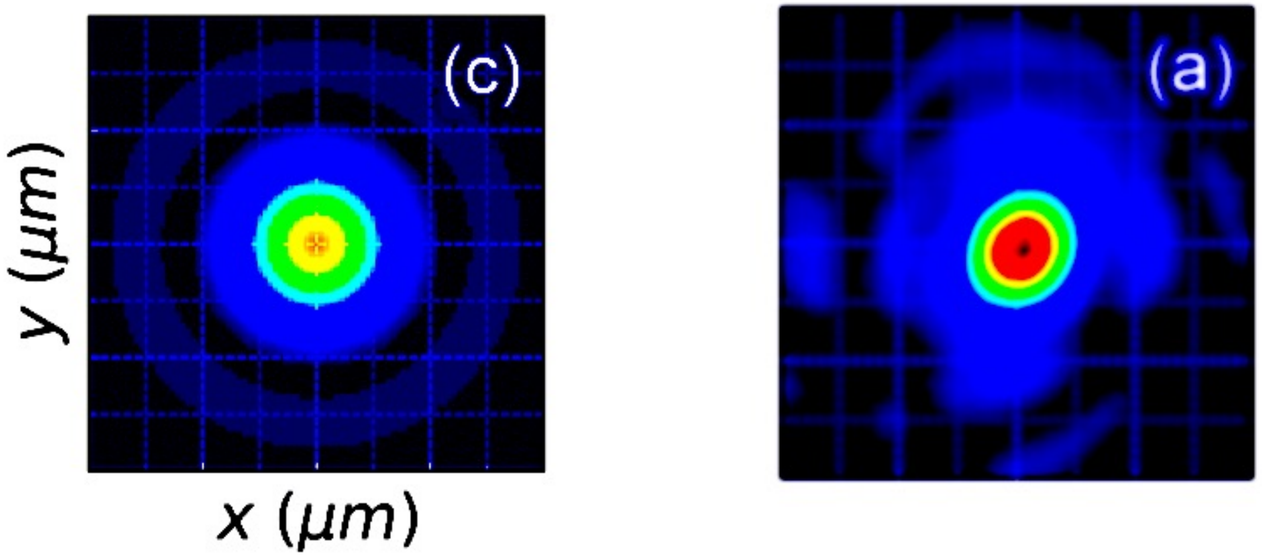
$$E(x,y,z,t) = \mathrm{Re}\left[\tilde{E}(x, y-y_0, z-z_0, t)\, T(x-ct)\, e^{ik_0(x-ct)}\right]$$



I. Moulanier et al., PoP 2026

Transverse laser description: expectation vs reality

Laser fluence on transverse planes



LWFA simulations
with symmetric laser:
- easier and faster to run
- easier and faster to analyse
- quantitatively less accurate

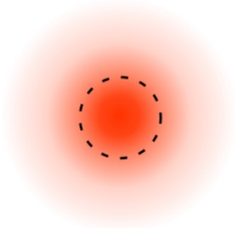
LWFA Simulations
with ”realistic” (asymmetric) laser:
- more cumbersome to run
- more difficult to analyse
- quantitatively accurate

I. Moulanier et al., J. Opt. Soc. Am. B 40(9), 2450-2461 (2023)

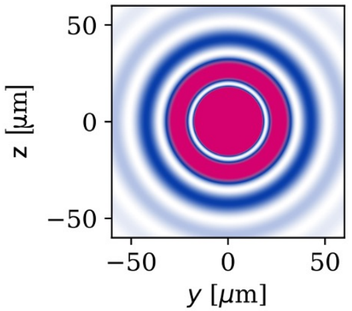
An increasing complexity can be added to transverse laser modelling (see J. Vieira's slides for PACRI Annual Meeting, and P. Tomassini's talk)

Expectation → **Reality**

Gaussian beam	Focused flattened Gaussian beam	Reconstructed Laguerre-Gauss with l=0	Reconstructed laser with asymmetries



Most LWFA literature

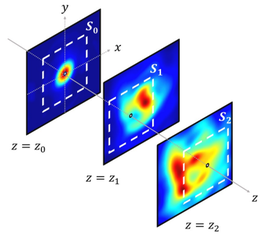


S. Jalas, PRL 2021,

M. Kirchen et al., PRL 2021,

P. Drobniak et al. PRAB 2023, Appl. Sciences 2026

T. L. Steyn et al., PRAB 2026



J. Ferri et al., SciRep 2016,

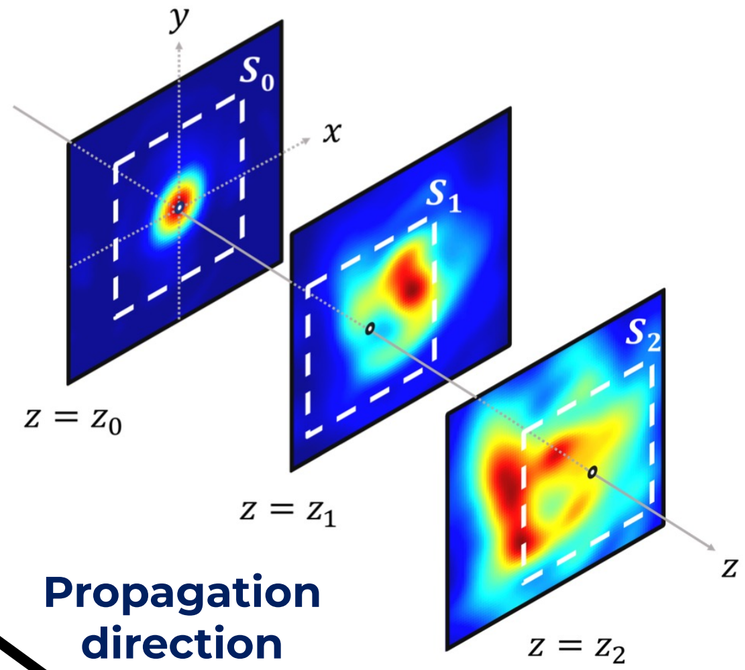
I. Moulanier et al., JOSA B (2023)

Caveat:

No STC are considered

LWFA PIC simulations can be performed with transverse laser field distributions reconstructed from measurements

Fluence images for laser field reconstruction



Propagation direction

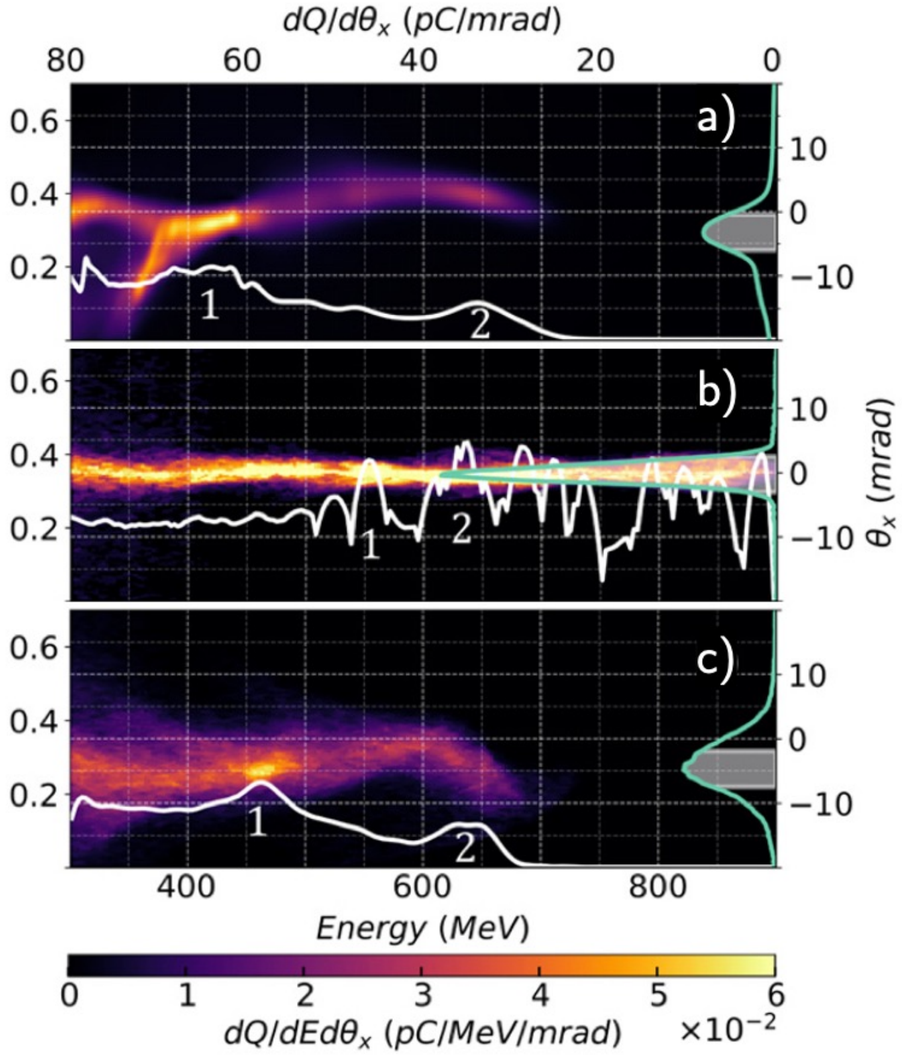
Gerchberg-Saxton Algorithm with Mode Decomposition (GSA-MD) in I. Moulanier et al., JOSA B 2023

Measured Electron spectrum

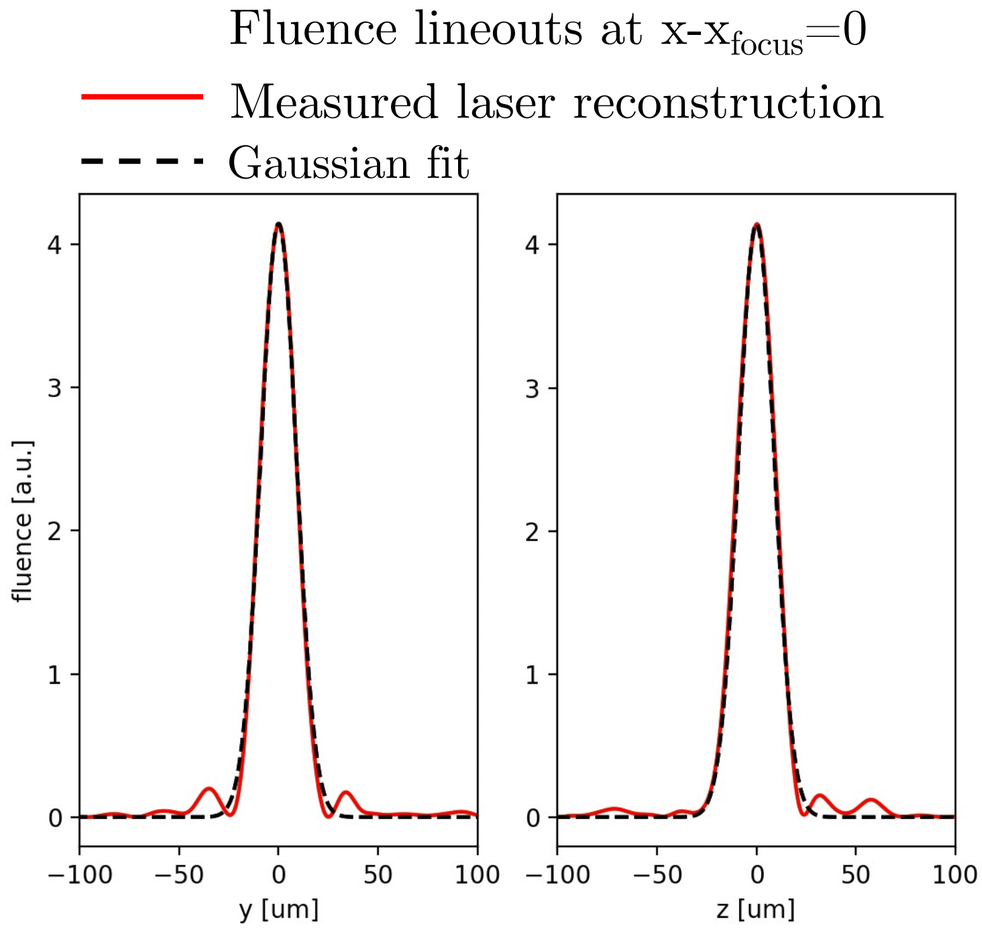
Simulation with Gaussian laser

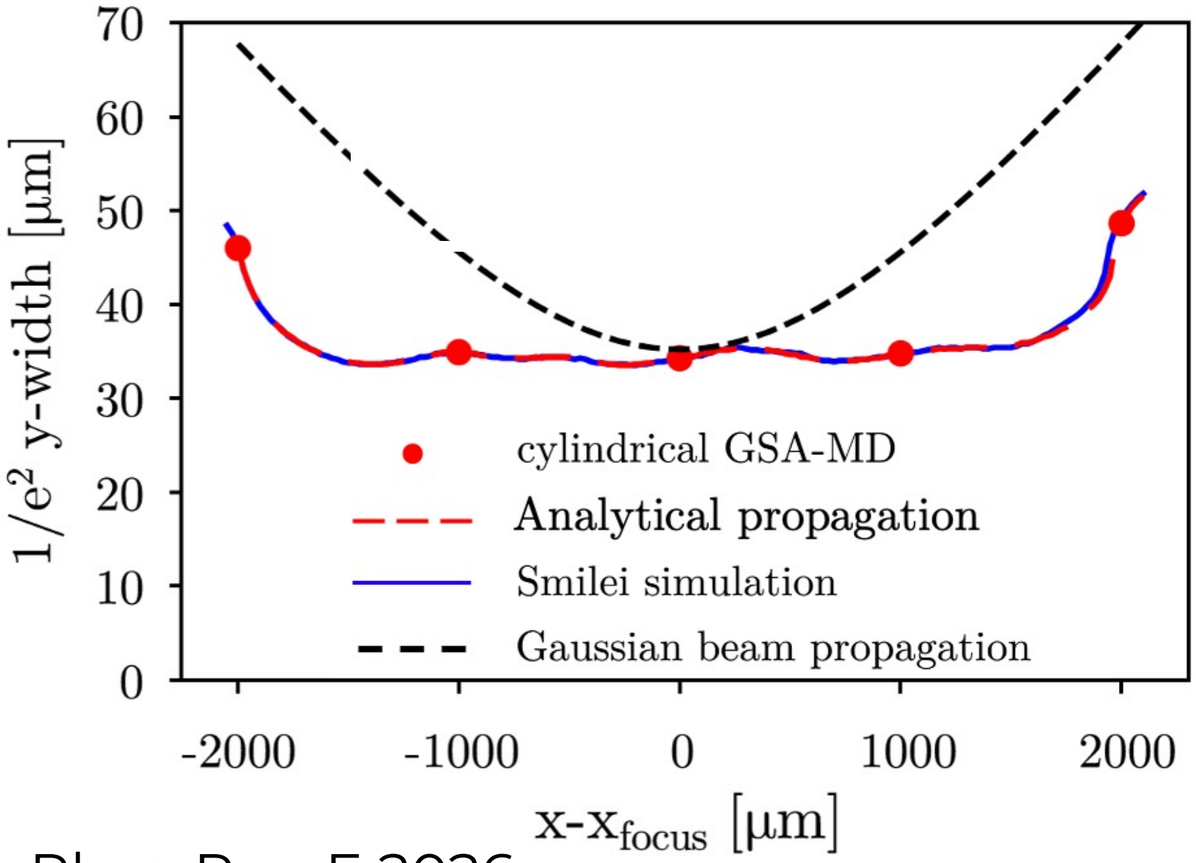
Simulation with reconstructed laser

I. Moulanier et al., Physics of Plasmas 2023



Vacuum propagation: ideal laser vs reconstructed laser

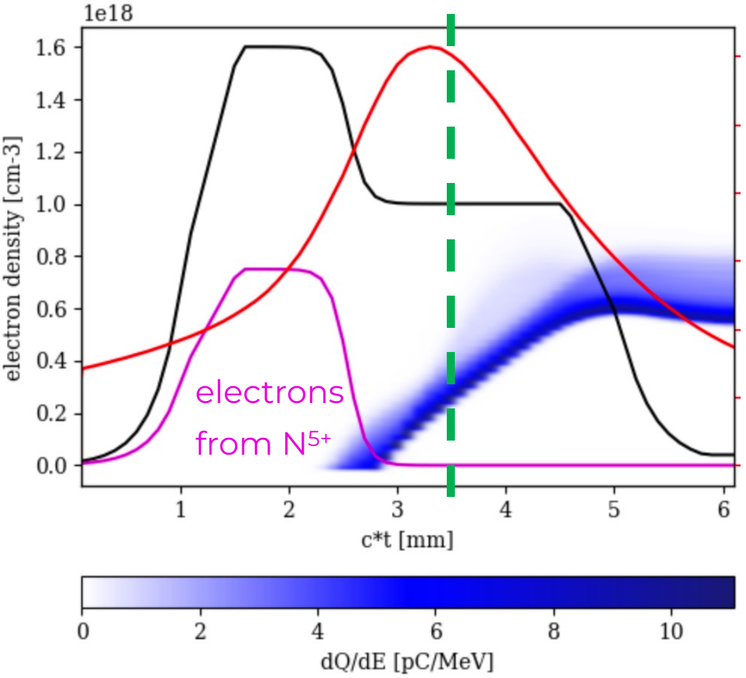




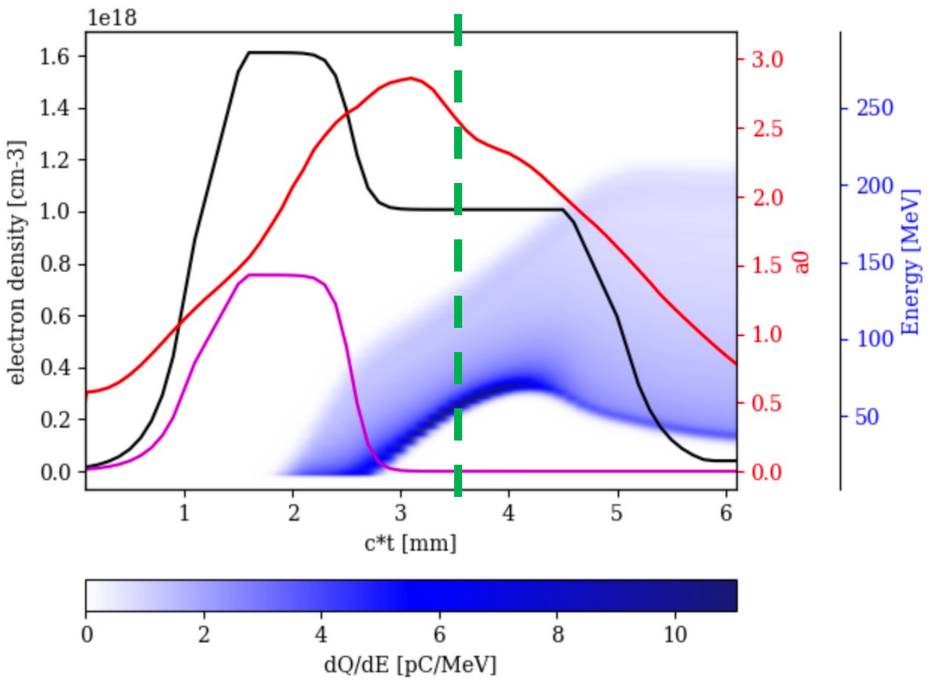
F. Massimo et al., Phys. Rev. E 2026

Gaussian vs reconstructed laser and ionization injection: laser evolution, e-injection and acceleration are completely different

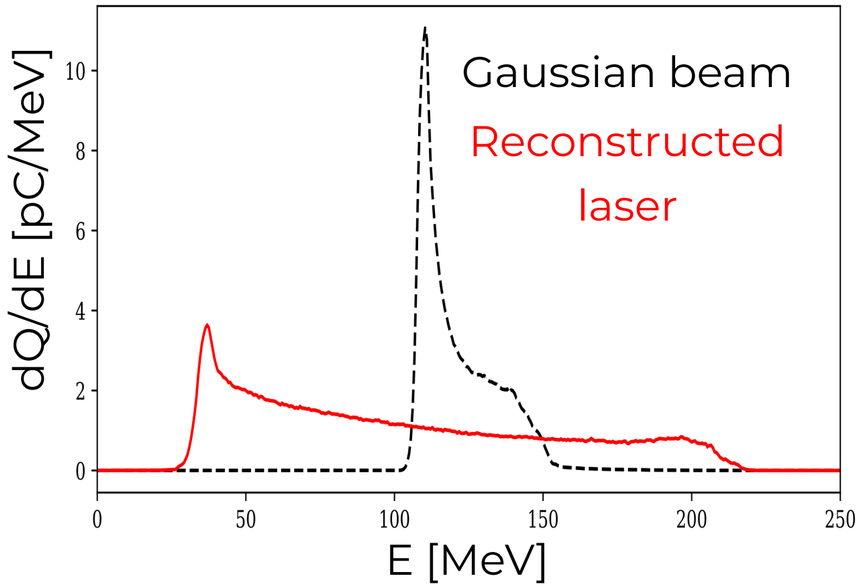
Gaussian beam
focal plane



LG modes
focal plane



Final
electron energy spectrum



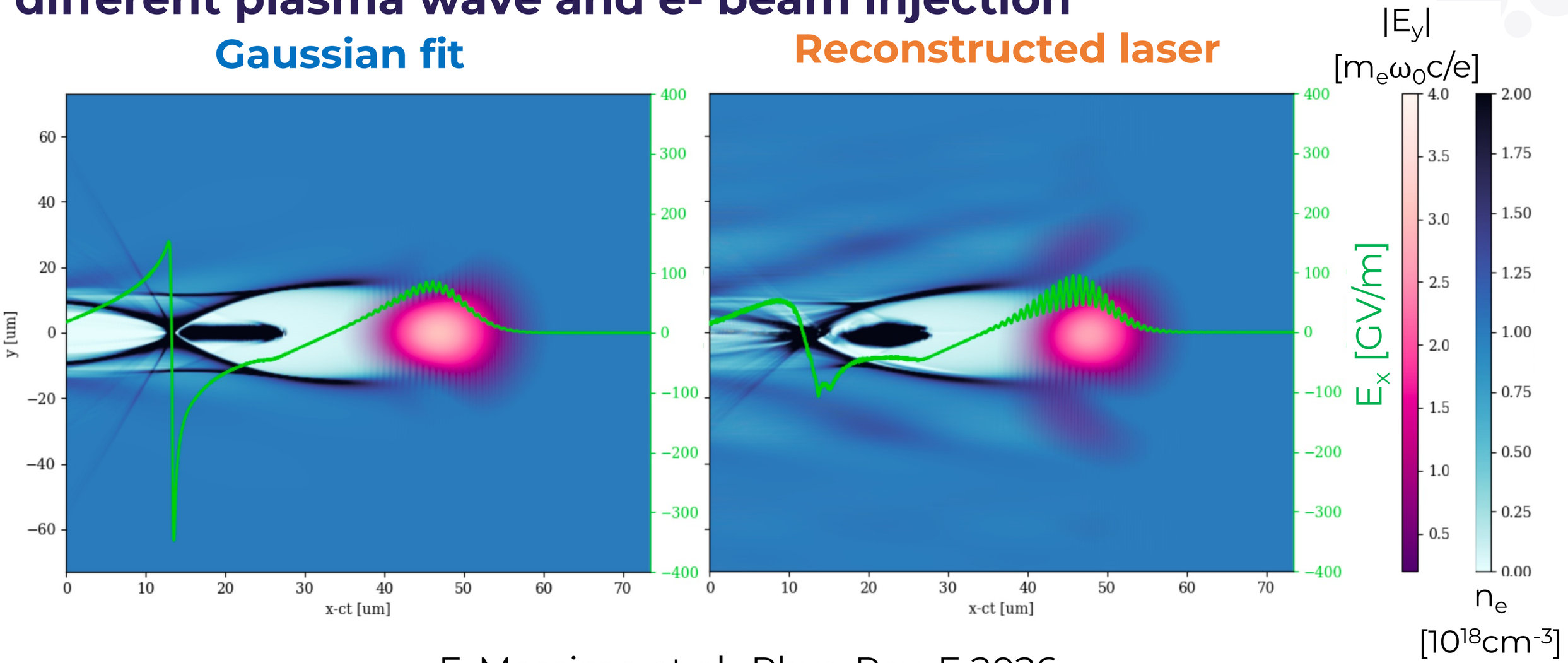
Caveat: viceversa,
a good working point for a realistic laser
may not be as good
with an idealized laser model

F. Massimo et al., Phys. Rev. E 2026

Gaussian vs reconstructed laser: different plasma wave and e- beam injection

Gaussian fit

Reconstructed laser



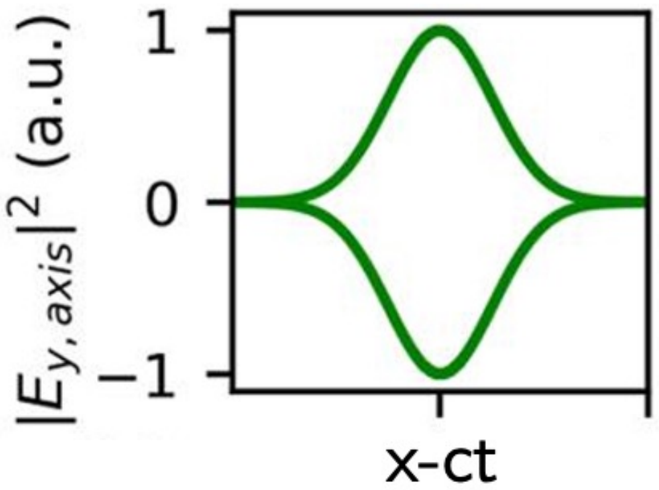
F. Massimo et al., Phys. Rev. E 2026

Temporal laser description: an experiment-based definition

Unchirped Gaussian pulse

I. Moulanier et al., PoP 2026

$$\mathrm{T(t)} = \exp\left[-\frac{t^2}{\tau^2}\right] \exp[i\omega_0 t]$$



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I. Moulanier et al., PoP 2026

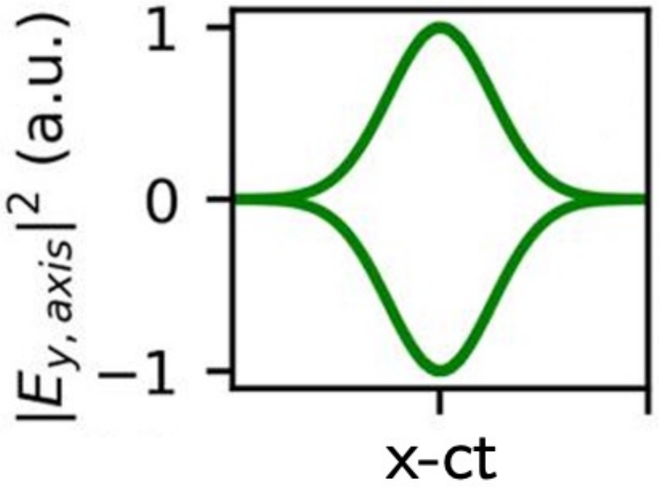
Unchirped Gaussian pulse

$$T(t) = \exp\left[-\frac{t^2}{\tau^2}\right] \exp[i\omega_0 t]$$

FFT

Chirped time spectrum

$$T_c(\omega)$$



Add spectral phase

$$\phi_c(\omega) = \sum_{n=0}^{+\infty} \phi_n \frac{(\omega - \omega_0)^n}{n!}$$

Spectral phase terms were experimentally set through a DAZZLER

Temporal laser description: an experiment-based definition

I. Moulanier et al., PoP 2026

Unchirped Gaussian pulse

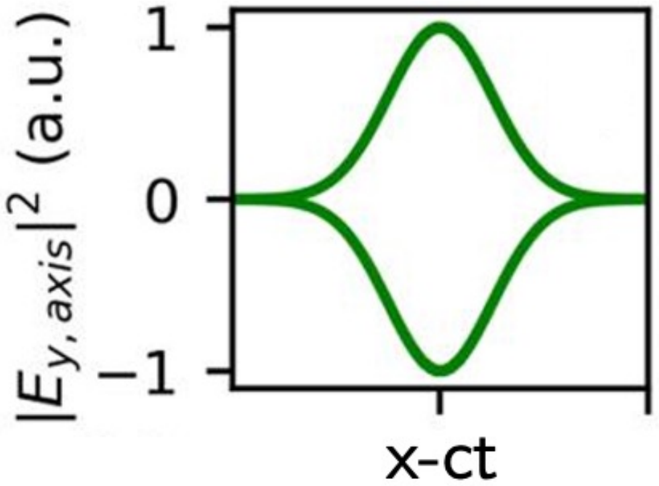
$$T(t) = \exp\left[-\frac{t^2}{\tau^2}\right]\exp[i\omega_0 t]$$

FFT →

Chirped time spectrum $T_c(\omega)$

IFFT →

Chirped time envelope $T_c(t)$



Add spectral phase ↑

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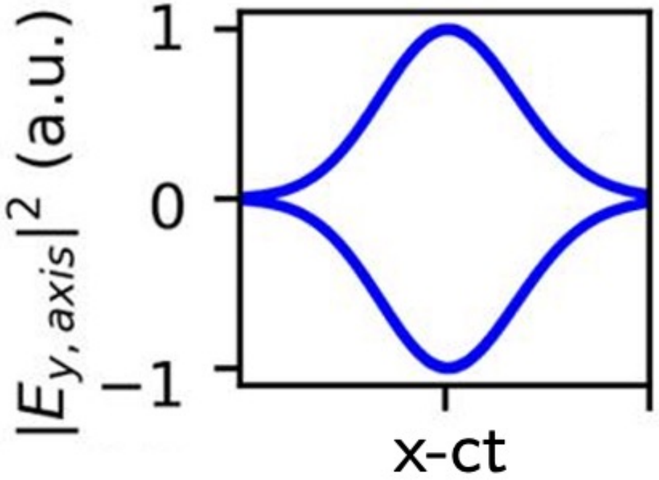

Spectral phase terms were experimentally set through a DAZZLER

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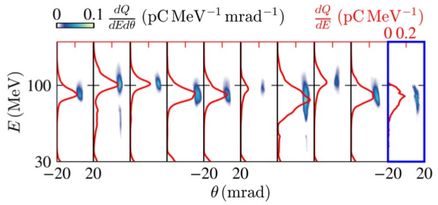


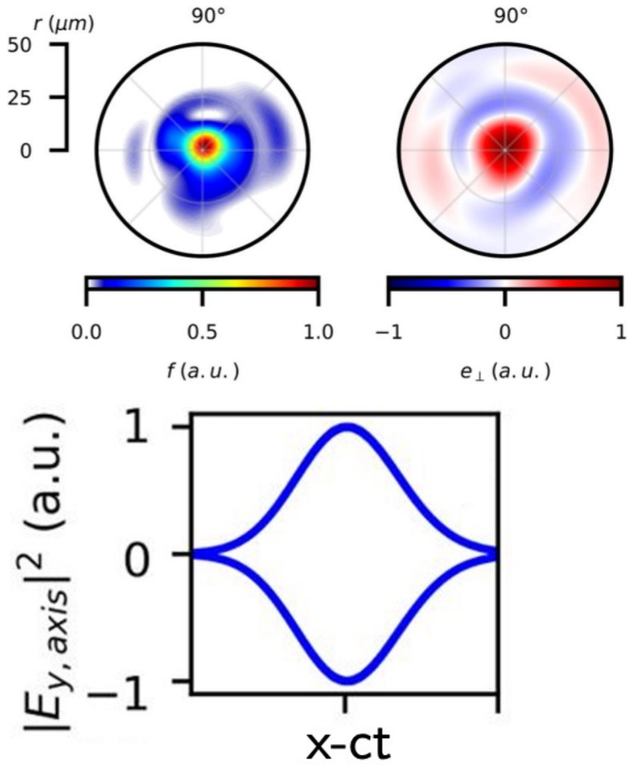
Combining the transverse and temporal laser description yields simulations in agreement with the LLC experiment

Transverse laser description

+

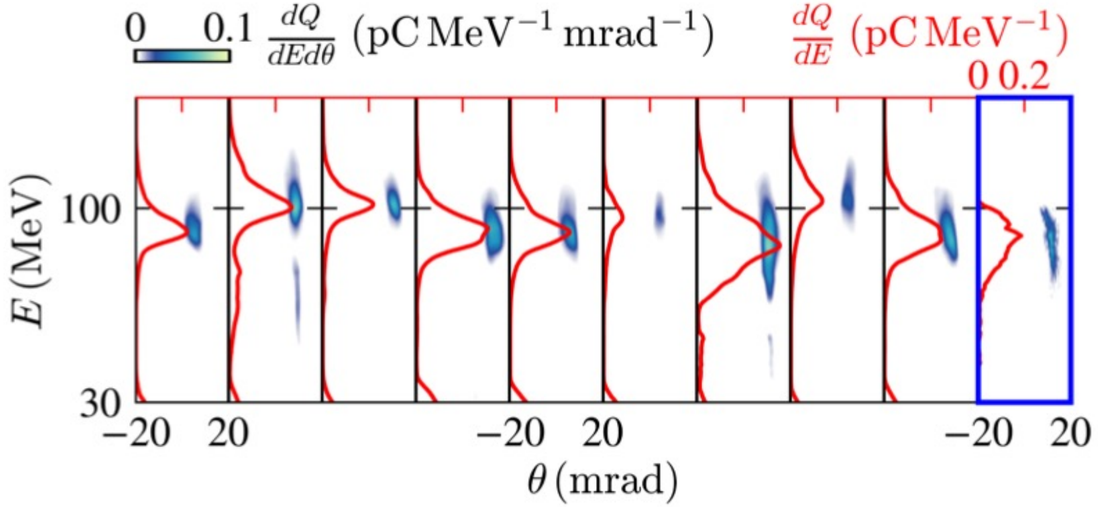
Temporal laser description

Modeling with the reconstructed laser



I. Moulanier et al., PoP 2026

Comparison PIC vs experiment

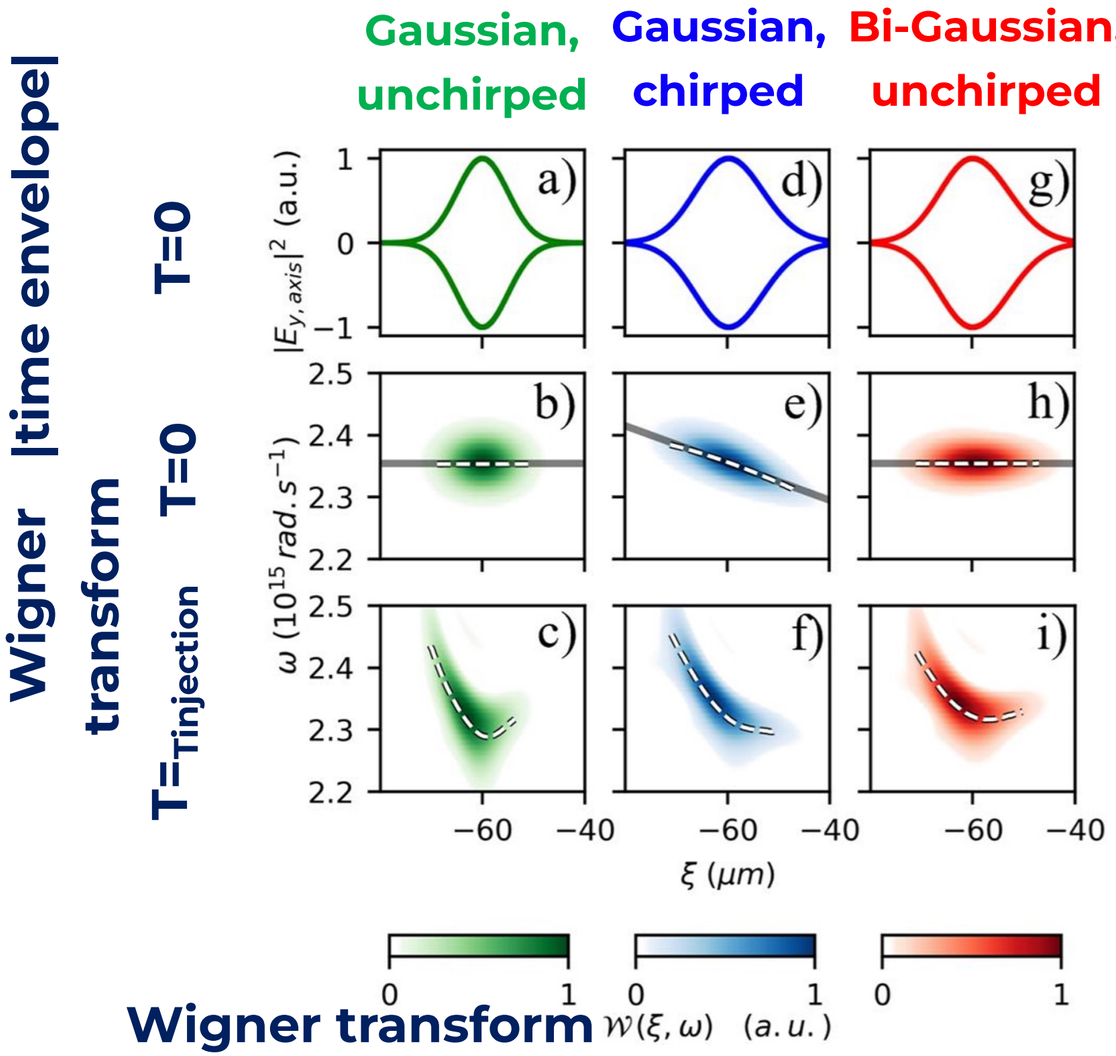


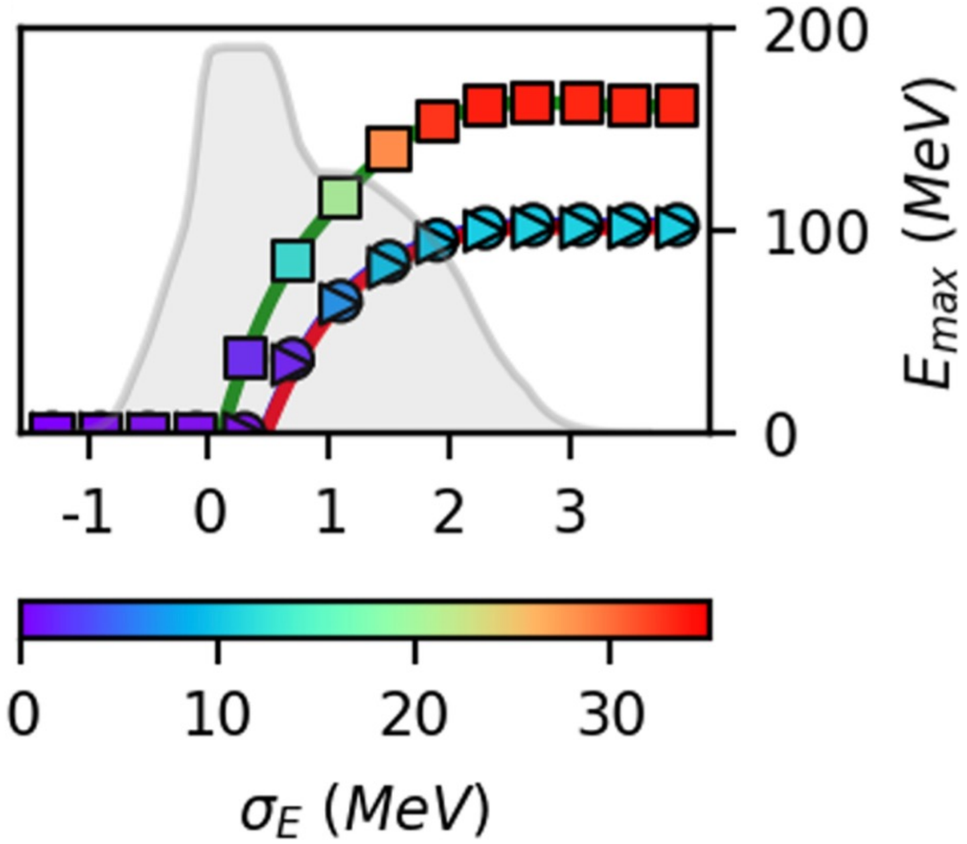
Measured optimized spectra

Simulated spectrum

M. Backhouse et al., PRAB 2025

Laser envelope effects in the working point found by the experiment





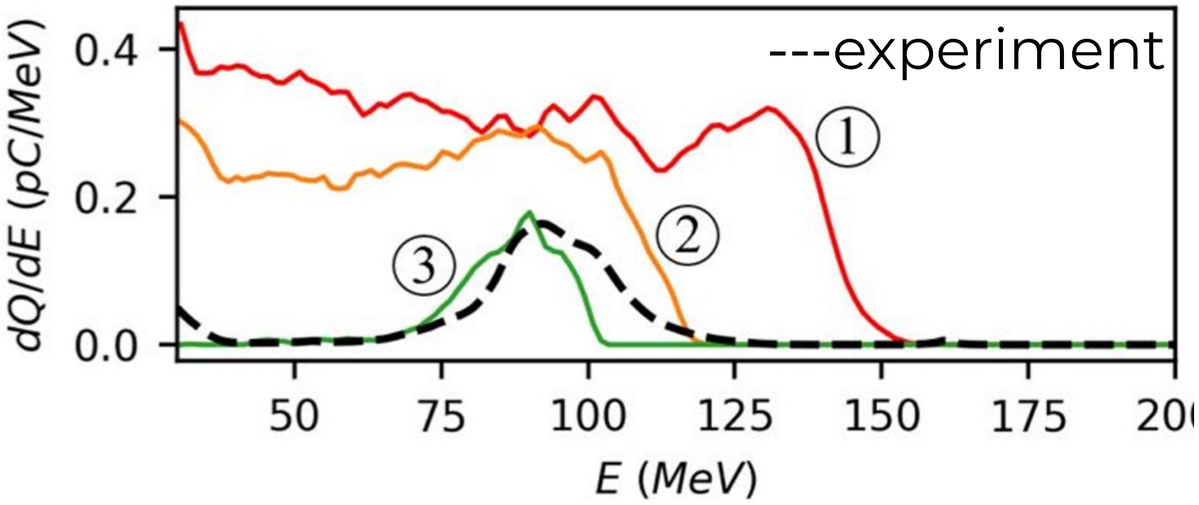
I. Moulanier et al., PoP 2026

Understanding the effect of the chirp parameter

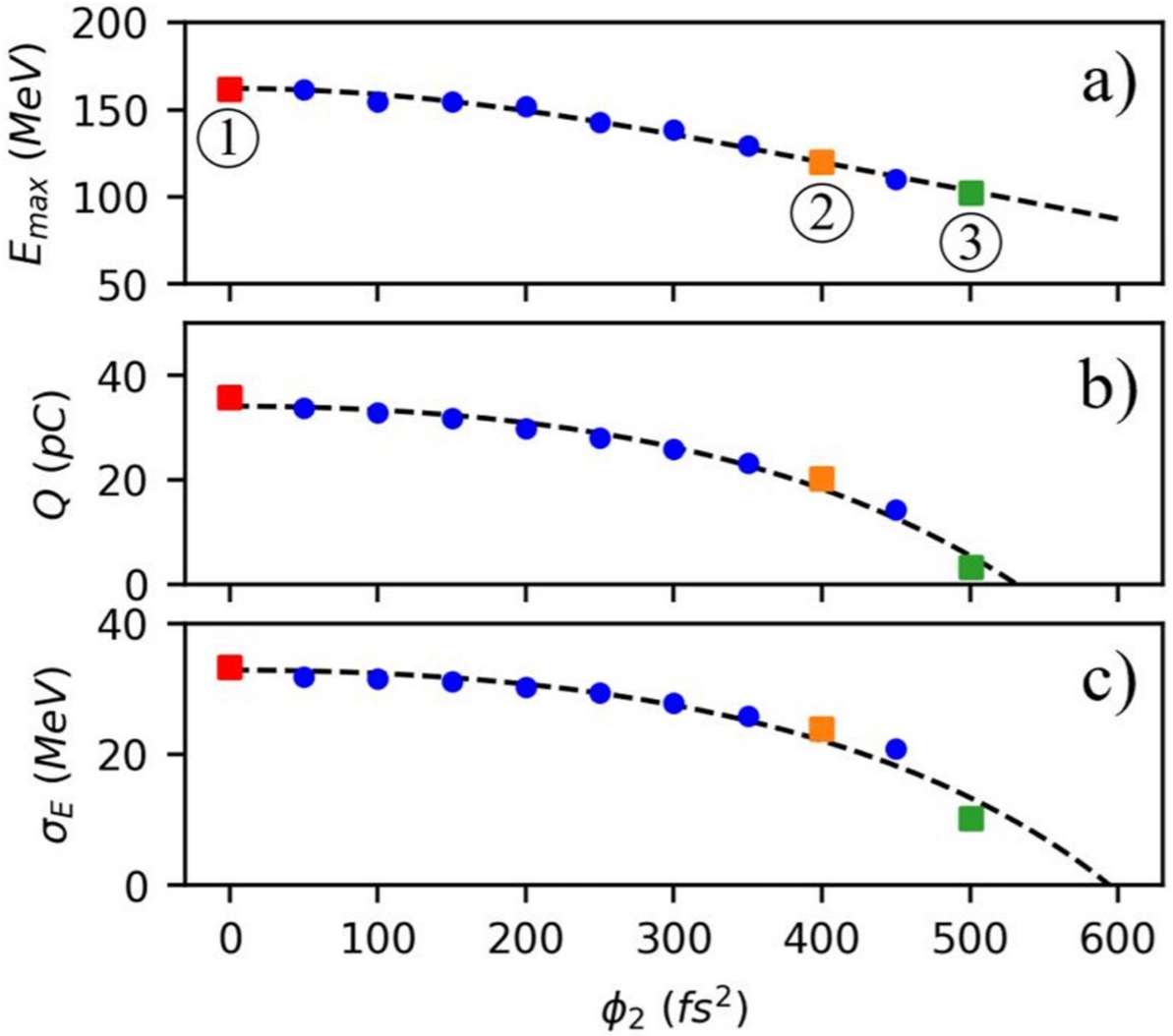
$\Phi_2 = 0\ fs^2$

$\Phi_2 = 400\ fs^2$

$\Phi_2 = 500\ fs^2$

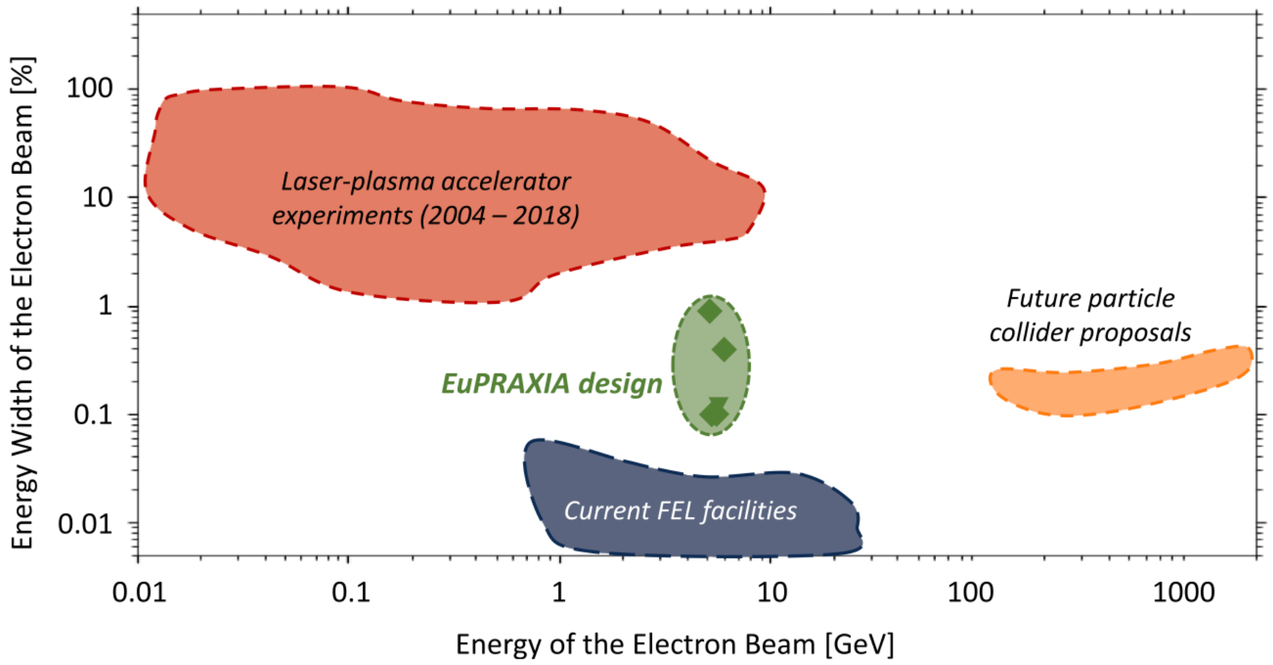


I. Moulanier et al., PoP 2026



Conclusions

EuPRAXIA Conceptual Design Report (2020)



- Understanding which laser features are « imperfections » and which are good features is critical in a given LWFA set-up to achieve high beam quality

- Recent workflows allowing to couple the transverse and temporal laser descriptions are enabling unprecedented predictive power for LWFA modeling

- Laser spectral phase manipulation is a new degree of freedom that can be used to find interesting LWFA working points, both experimentally and numerically

Acknowledgements

Experiment @ LLC

C. C. Cobo, F. Filippi, C. Gustafsson, E. Lofquist , K. Svendsen , M. J. V. Streeter, R. J. Shalloo, O. Vasilovici, C. Ballage, S. J. D. Dann, C. D. Murphy, Z. Najmudin, S. Dobosz Dufrénoy, O. Lundh

Experiment @ Apollon

C. Ballage, O. Vasilovici, A. Gremaud, S. Dobosz Dufrénoy, N. Delerue, L. Bernardi, A. Mahjoub, A. Specka, G. Maynard

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(Virtual Laplace) made by GENCI, the use of the meso-scale HPC "3Lab Computing" hosted at École polytechnique and administrated by the Laboratoire Leprince-Ringuet, Laboratoire des Solides Irradiés et Laboratoire pour l'Utilisation des Lasers Intenses.

Extra slides

General lasers have spatio-temporal couplings (see J. R. Pierce et al., PRX 2023)

Laser envelope form into wave equation in vacuum

$$E(x,y,z,t) = \mathrm{Re}\left[\tilde{\mathcal{E}}(x, y-y_0, z-z_0, t)\; e^{ik_0(x-ct)}\right]$$

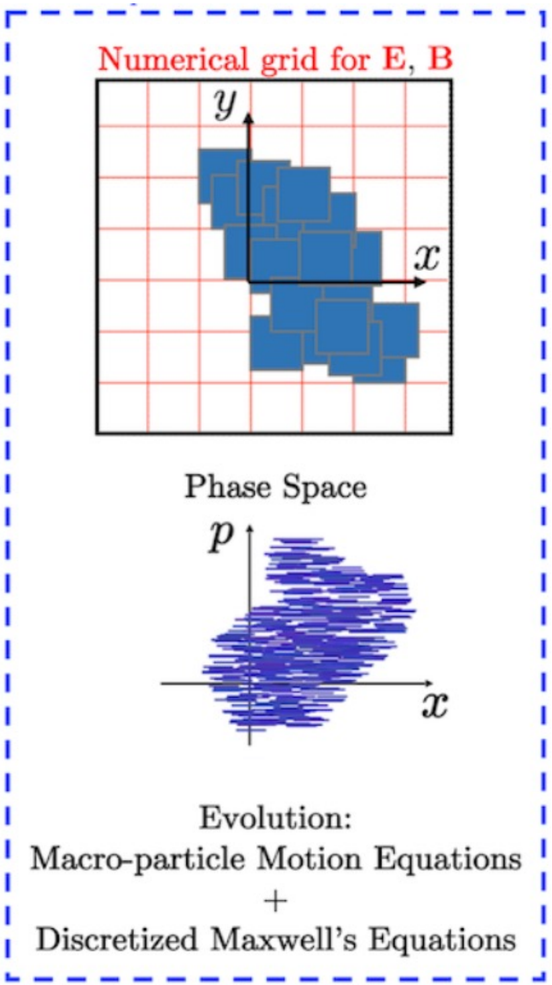
Comoving coordinates

ξ=x-ct, s=x

Envelope equation in comoving coordinates

$$\nabla_\perp^2 \tilde{\mathcal{E}} + 2ik_0 \frac{\partial \tilde{\mathcal{E}}}{\partial s} + 2\frac{\partial^2 \tilde{\mathcal{E}}}{\partial \xi \partial s} + \frac{\partial^2 \tilde{\mathcal{E}}}{\partial s^2} = 0$$

Quick recap: Particle in Cell (PIC) method



PIC time loop

Field Interpolation

$$[\mathbf{E}, \mathbf{B}] \rightarrow [\mathbf{E}_p, \mathbf{B}_p]$$

Maxwell Solver

$$\partial_t \mathbf{E} = -\mathbf{J} + \nabla \times \mathbf{B}$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

Δt

Particle Pusher

$$d_t \mathbf{p}_p = q_s \left(\mathbf{E}_p + \mathbf{v} \times \mathbf{B}_p\right)$$

$$d_t \mathbf{x}_p = \mathbf{p}_p / \left(m_s \gamma\right)$$

Current Projection

$$[\mathbf{x}_p, \mathbf{p}_p] \rightarrow [\rho_s, \mathbf{J}_s]$$

https://smileipic.github.io/Smilei/Understand/algorithms.html