Recent progress in the modeling of laser wakefield acceleration

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Smilei development team

A. Beck, G. Bouchard, M. Grech, M. Lobet, F. Pérez, C. Prouveur, T. Vinci

EARLI Project

D. F. G. Minenna, L. Batista, B. Cros, C. Simon-Boisson, S. Bethuys, B. Bolzon, A. Jeandet, S. Marini, I. Moulanier, P. A. Phi Nghiem, N. Pichoff, S. Ricaud, and C. Simon

AWAKE Project

P. Muggli, E. Gschwendter, J. Farmer

Outline

- Motivation: multi-stage laser wakefield acceleration (LWFA)

- Reconstruction of the laser field -> Realistic simulations

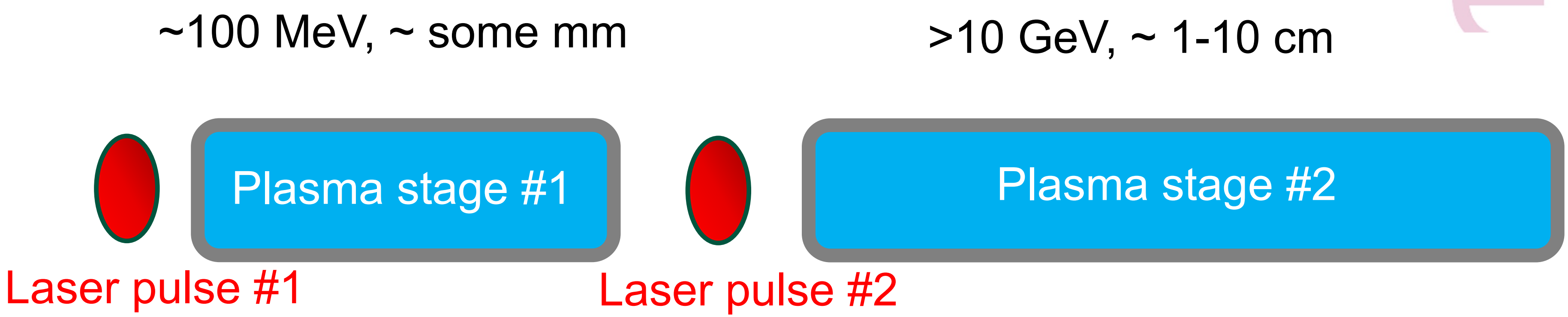
- Fast modelling of LWFA: envelope modeling
    - adding ionization
    - adding perfectly matched layer boundary conditions
    - reducing the effects of Numerical Cherenkov radiation

- Fast PIC modelling: Smilei on GPU

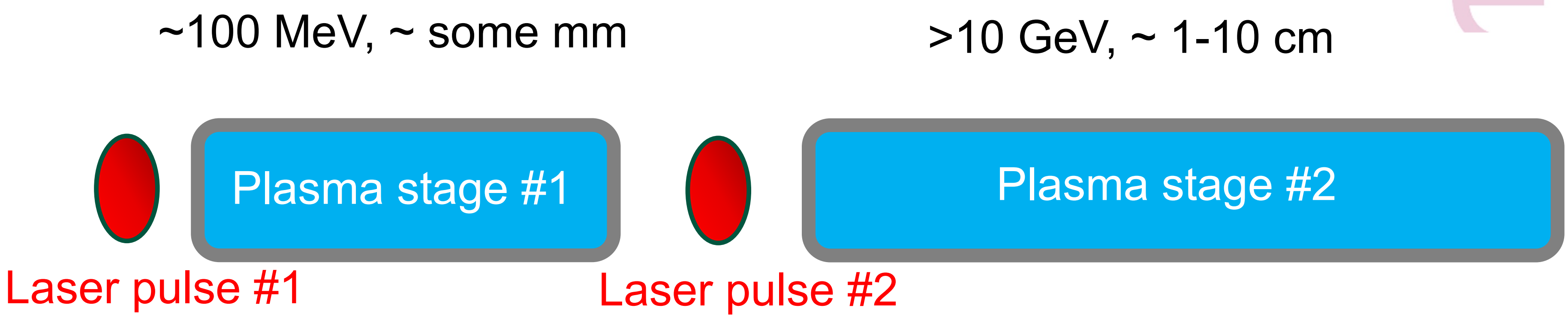
- Fast dataset generation, optimization

Motivation: multi-stage LWFA

Multi-stage laser wakefield acceleration: let's start from 2 stages



Multi-stage laser wakefield acceleration: let's start from 2 stages



Modeling:
- Fluid simulation of plasma formation
- PIC simulation of injection and acceleration

Challenges:
- Long simulation
- Numerical Cherenkov radiation
- Realistic simulations

Modeling:
- Beam dynamics simulation for beam transport

Challenges:
- Interface between PIC codes

Modeling:
- Fluid simulation of channel formation
- PIC simulation of injection and acceleration

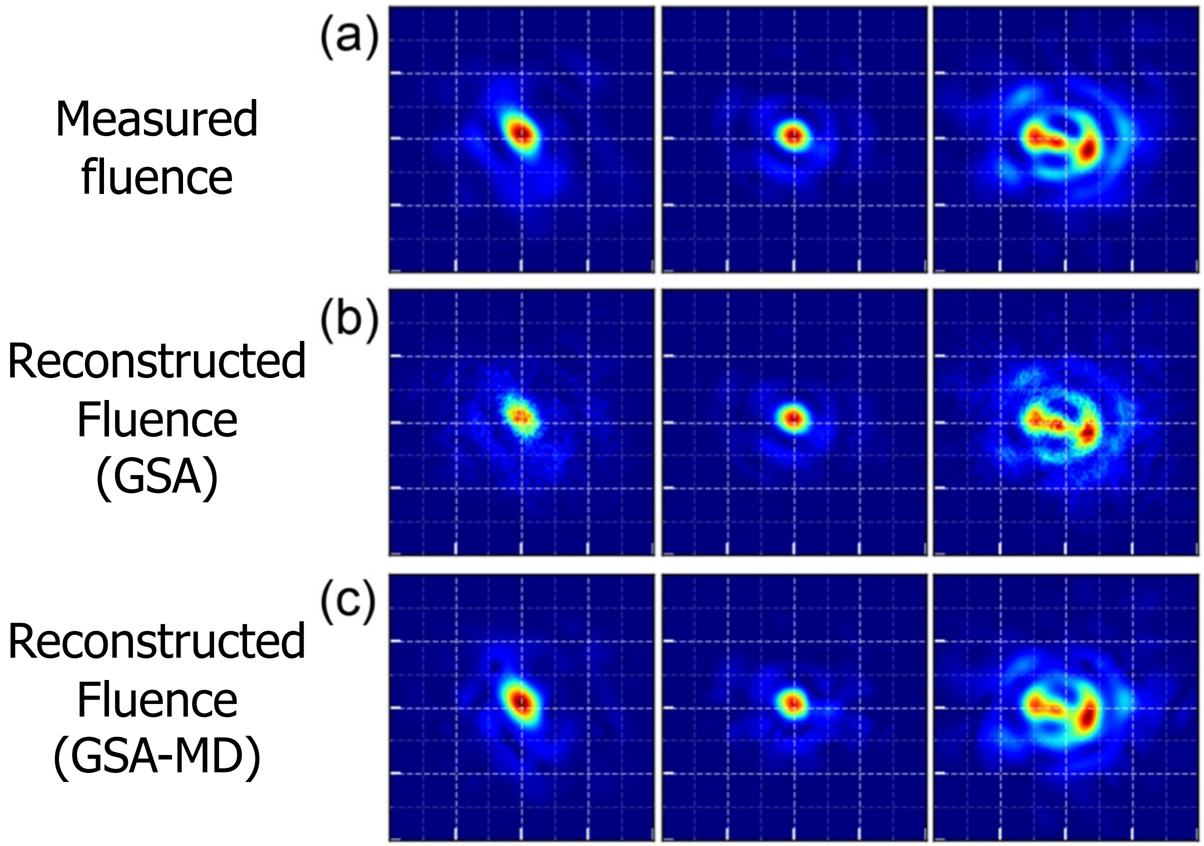
Challenges:
- Even longer simulation
- Numerical dephasing
- Boundary conditions
- Numerical Cherenkov radiation
- Realistic simulations

Addressed in this talk

Reconstruction of the laser field → realistic simulations

Gerchberg-Saxton algorithm with modes decomposition (GSA-MD)

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



See I. Moulanier's poster!

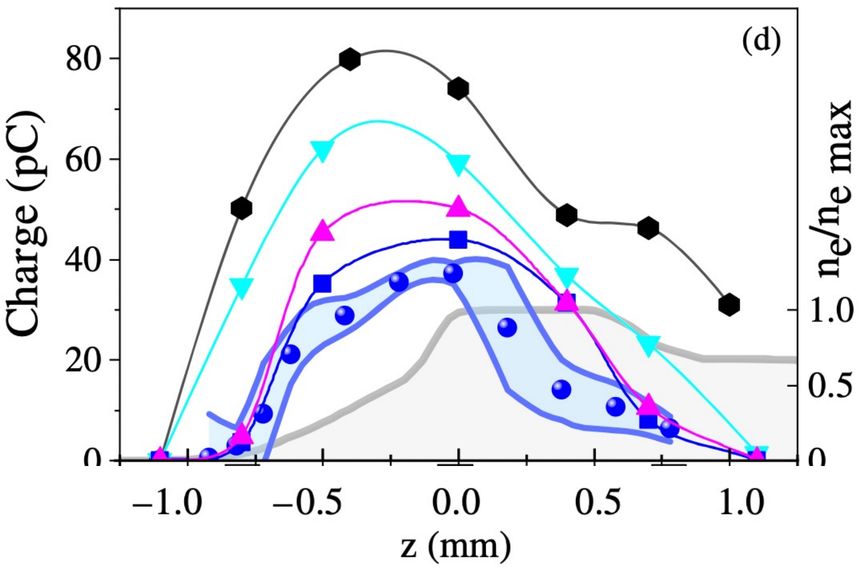
A deeper physical understanding with GSA-MD+PIC simulations

L. Dickson et al., Phys. Rev. Accel. Beams **25**, 101301 (2023)

Experiment

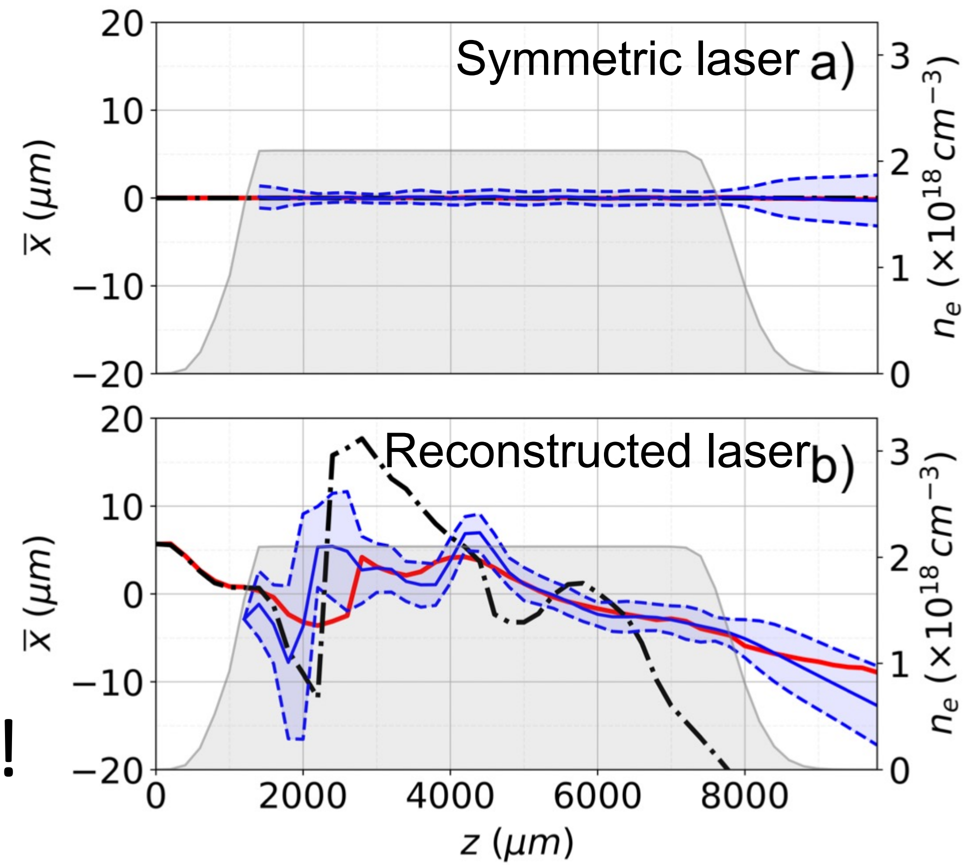
Ideal laser simulation

Realistic laser simulation



See I. Moulanier’s poster!

I. Moulanier et al, Phys. Plasmas 30 (2023) 5, 053109



Fast modeling of LWFA: envelope modeling and Smilei on GPU

Smilei)

A collaborative, open source
multi-purpose Particle in Cell code

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

User-friendly
- online: documentation, tutorials
- Python input/output
- quick visualisation library
- teaching platform
- bi-annual training workshop

High Performance
- MPI + OpenMP parallelization
- dynamic load balancing
- adaptive vectorization
- macro-particle merging

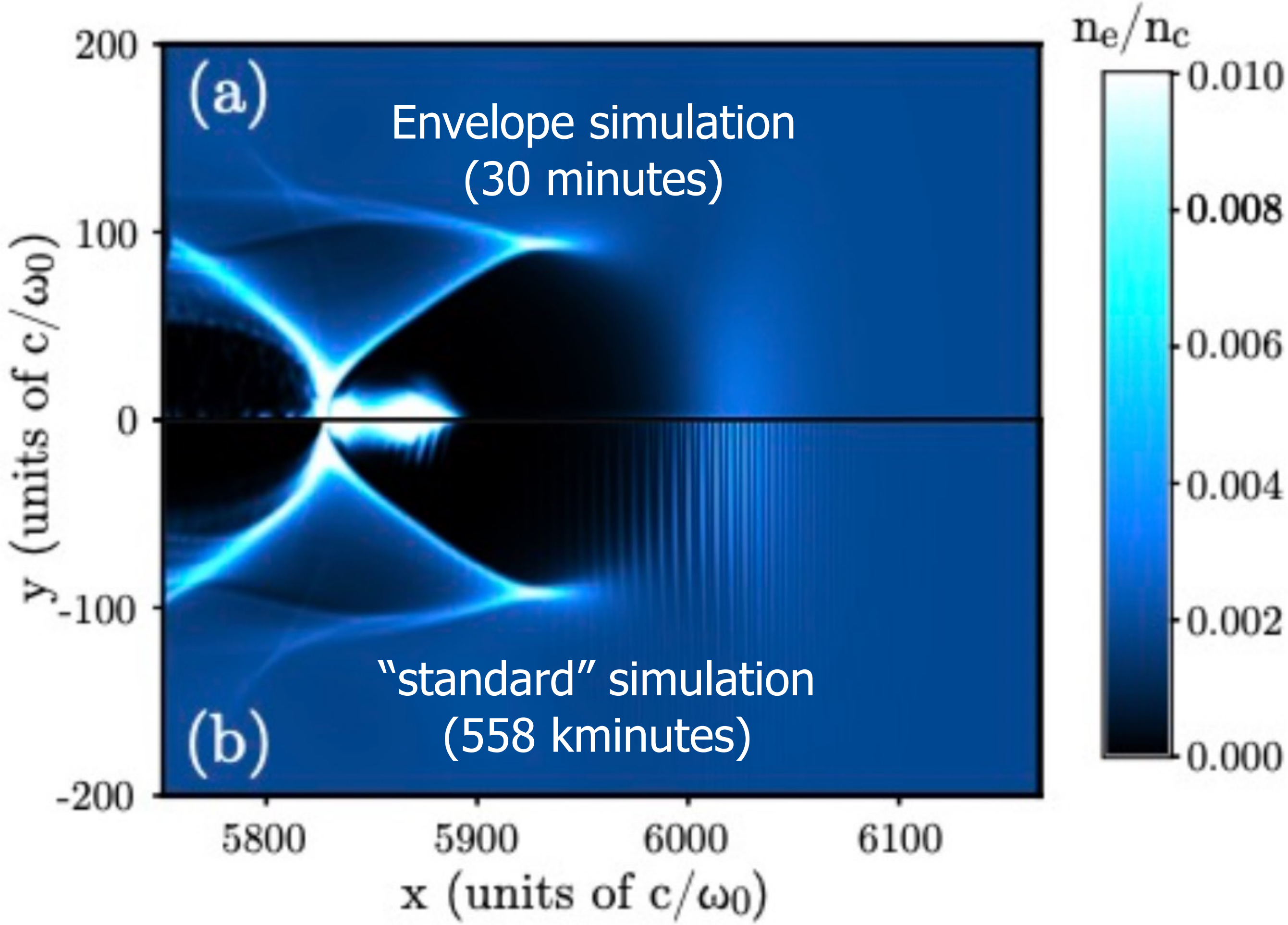
Multi-physics
- 1D, 2D, 3D, quasi-3D geometries
- ionization, collisions
- strong-field QED
- laser envelope model
- envelope relativistic ADK ionization
- relativistic beam field initialization
- B-TIS3 anti-Cherenkov interpolation

High quality
- developers: experts of physics and HPC
- continuously benchmarked
- GitHub bug reporting
- OpenPMD standard

Next Smilei Workshop: Prague, 8-10 Nov 2023
https://indico.math.cnrs.fr/event/9577/

MAISON DE LA SIMULATION

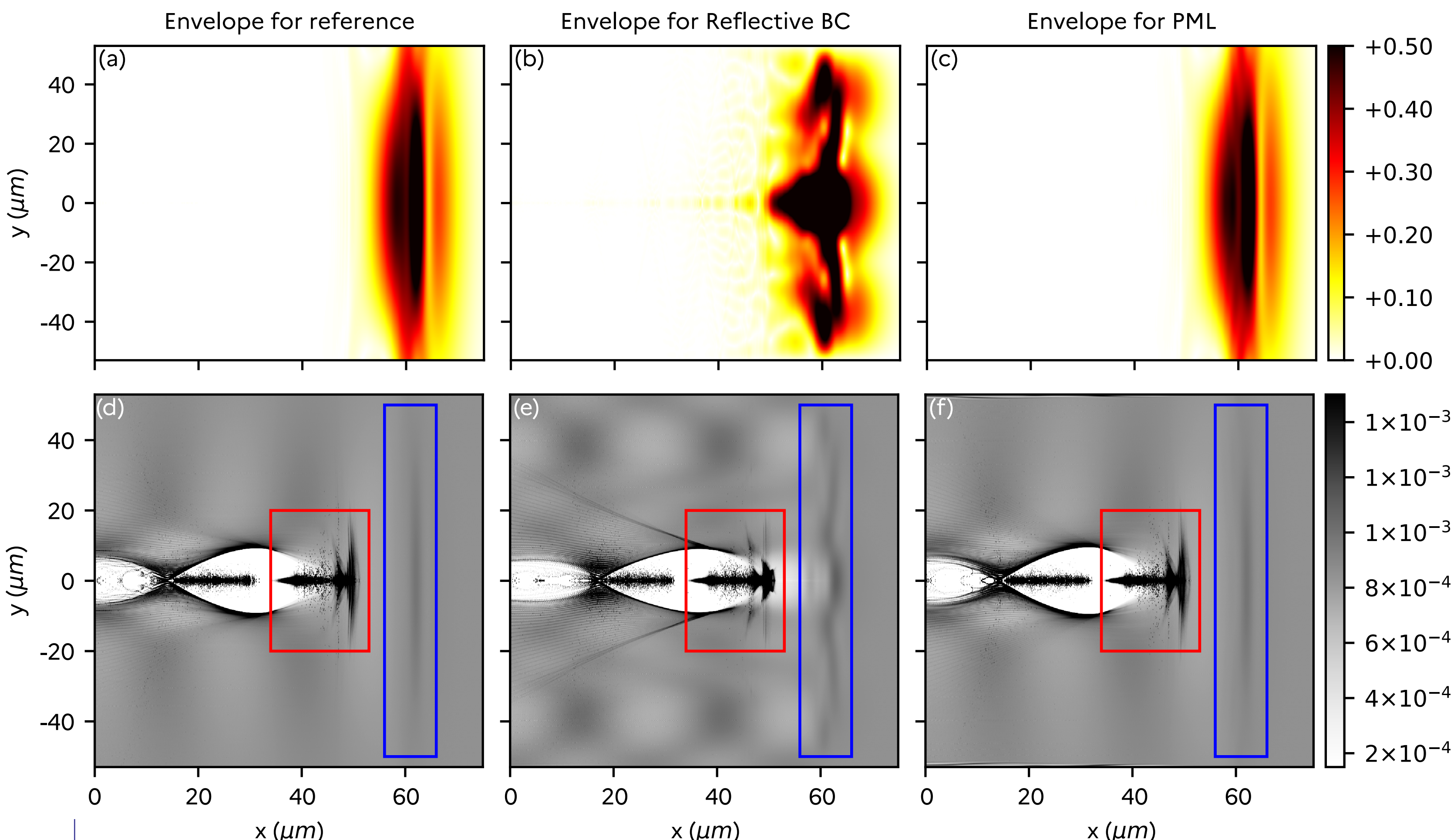
Fast ionization modeling through a laser envelope model



F. Massimo et al., Phys. Rev. E **102**, 033204 (2023)

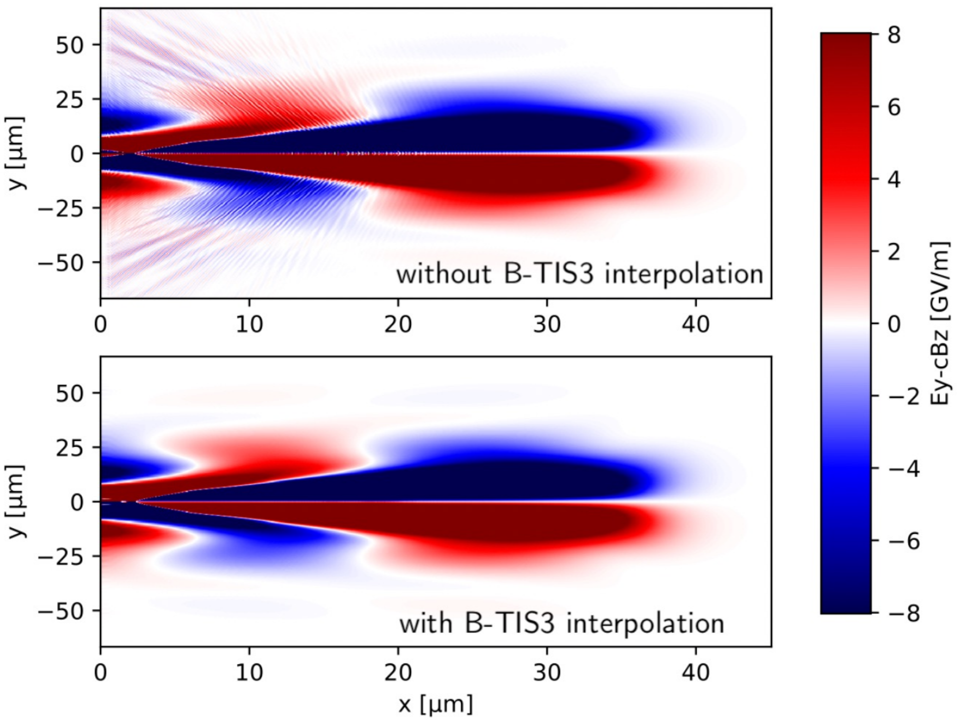
Envelope modeling: adding perfectly matched layers

G. Bouchard et al., in preparation (2023)



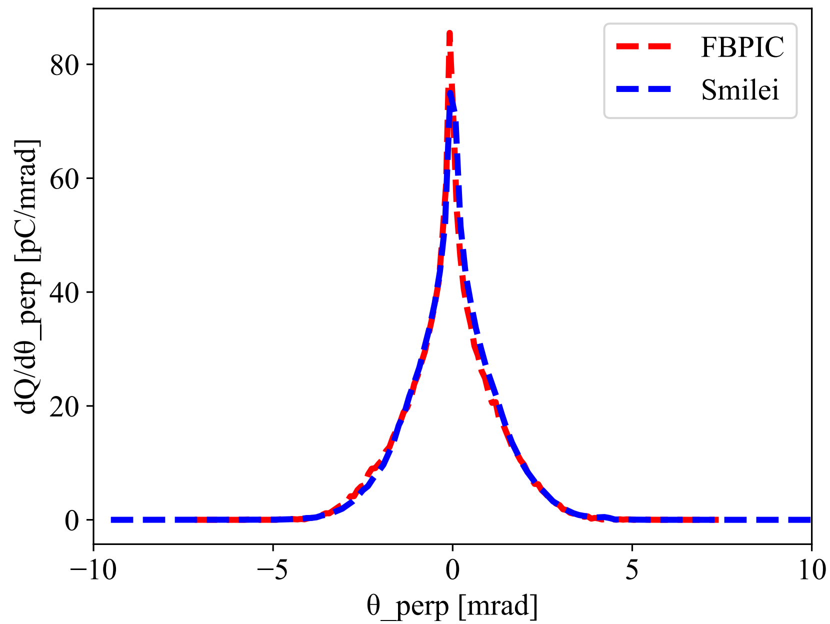
Envelope modeling: reducing the effects of numerical Cherenkov Radiation

No spectral solver is used!



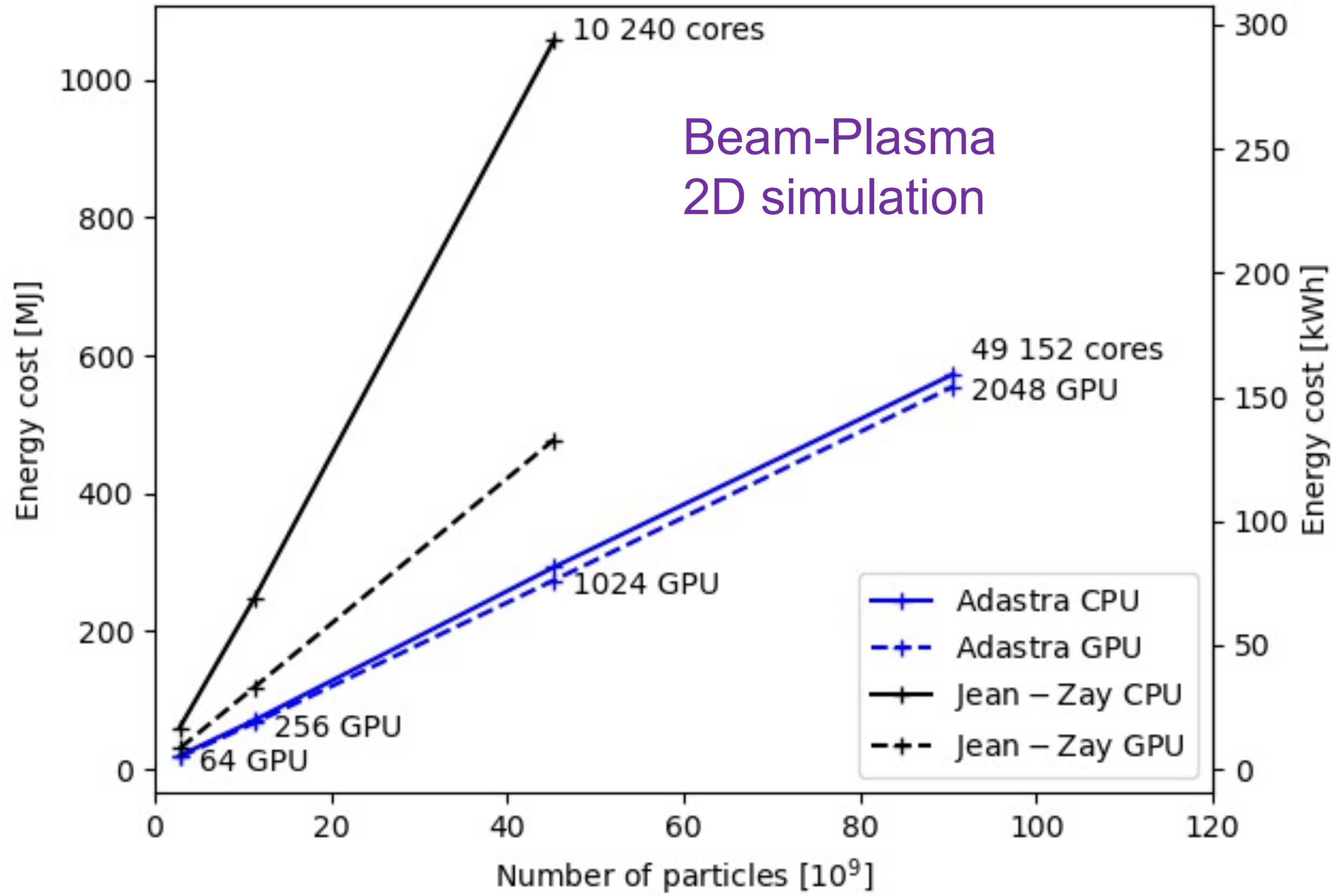
B-TIS3 scheme from
P.-L. Bourgeois and X. Davoine,
Journal of Plasma Physics 89 , 2 (2023)

Divergence and emittance
With and without a spectral code
after 7 mm of propagation



Quick simulations: Smilei porting on GPU is ongoing

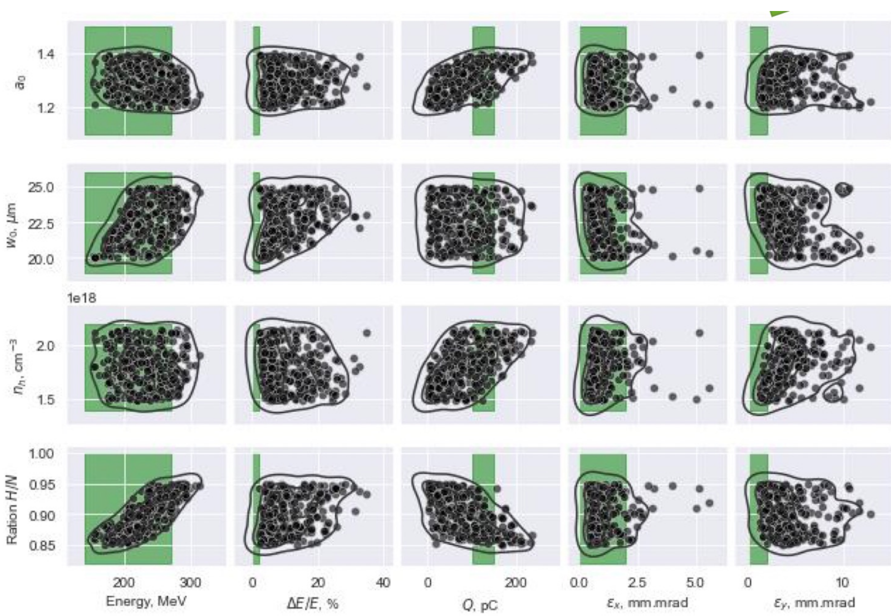
First release with initial GPU features planned for November



Fast dataset generation, optimization

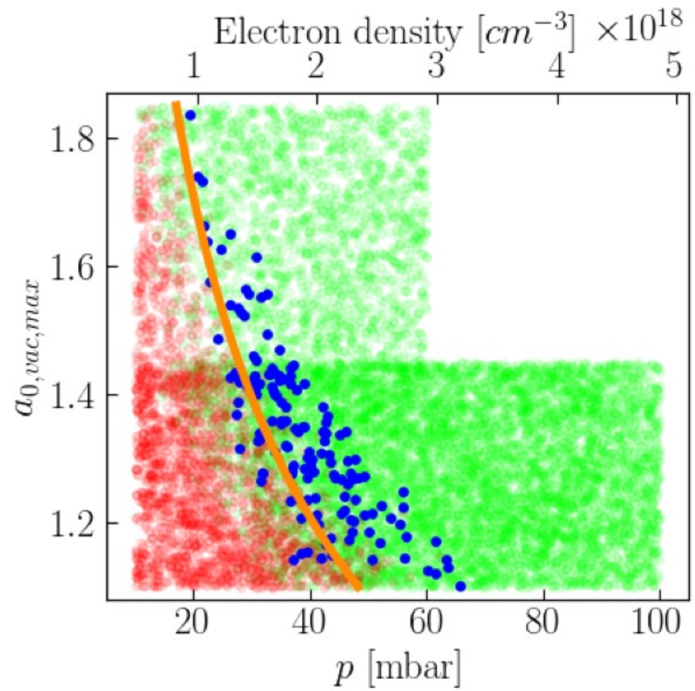
Random scan dataset generation for machine learning

D. Minenna et al.,
EuroNNAc Special Topics Workshop (2022)



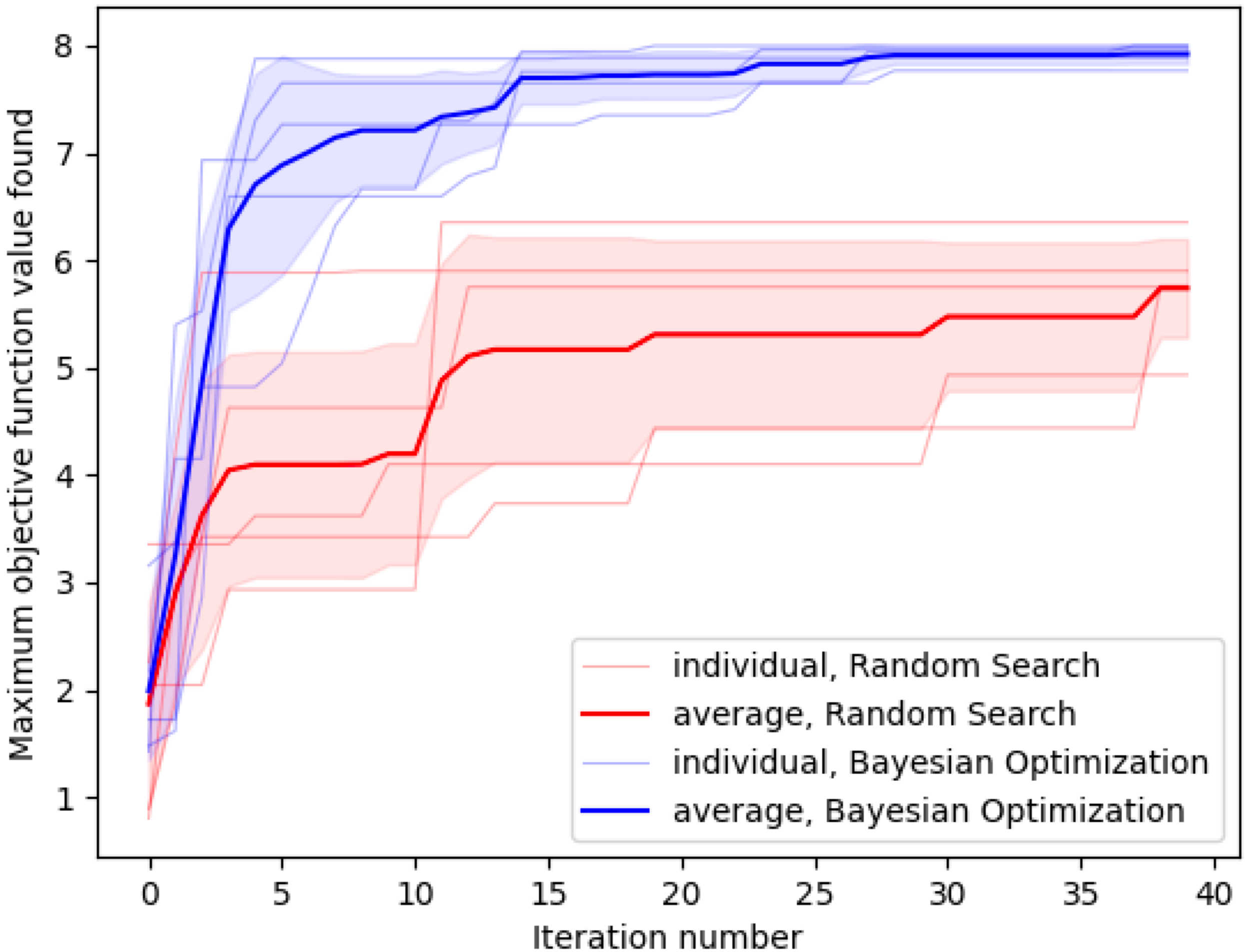
See S. Marini's poster!

P. Drobniak et al.,
Phys. Rev. Accel. Beams (2023)



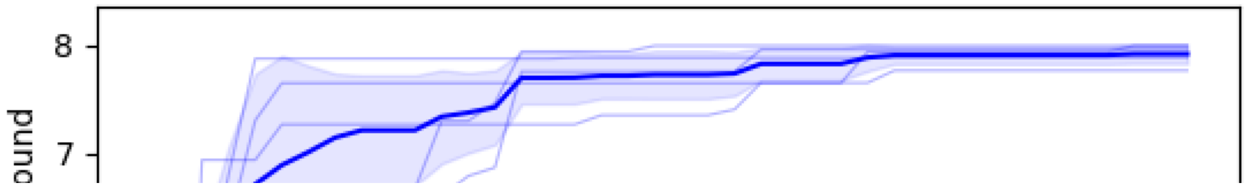
See V. Kubytsky's poster!

Comparison optimization methods possible with fast simulations

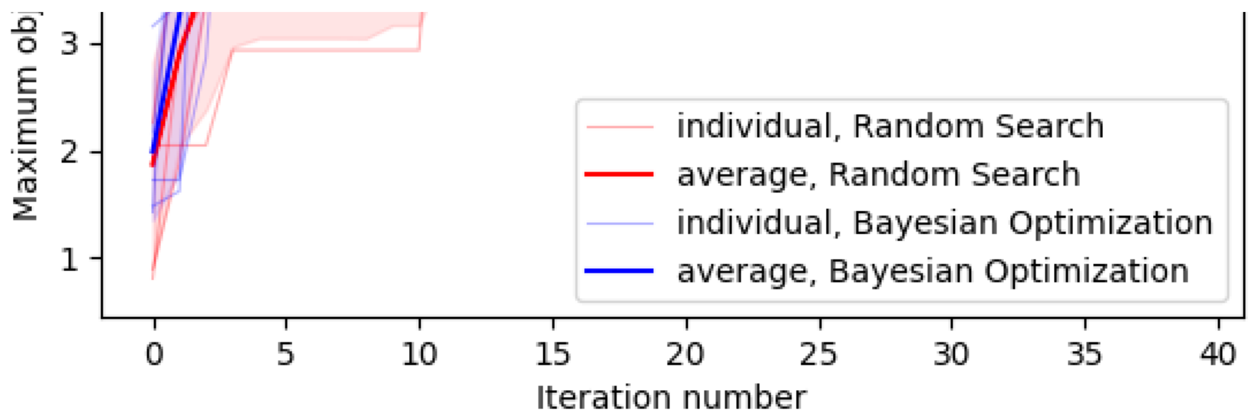


Same optimized function ($\sqrt{Q} * E/\Delta\mathrm{E}$) from S. Jalas et al, PRL 2020

Comparison optimization methods possible with fast simulations



How do BO compares with performances of other algorithms?
E.g. genetic algorithms, CMA-ES
Are we neglecting other efficient techniques?



Same optimized function ($\sqrt{Q} * E/\Delta\mathrm{E}$) from S. Jalas et al, PRL 2020

Conclusions

- Multistage LWFA offers considerable modeling challenges

- Combinations of different techniques will be necessary to face these challenges

- Recent progress in realistic simulation: GSA-MD, study of asymmetries effects

- Envelope modeling can be one of the techniques to have fast simulations

- Recent progress in envelope modeling: ionization, PML (available in Smilei)

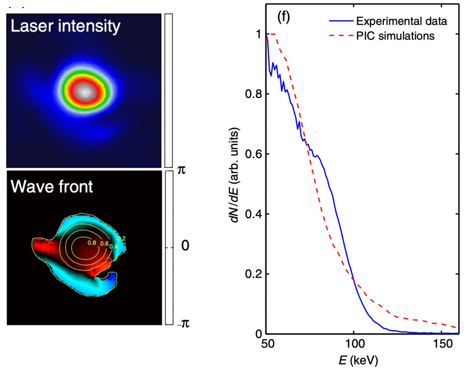
- Non spectral scheme B-TIS3 to reduce effects of numerical Cherenkov radiation is compatible with envelope modeling (available in Smilei)

- GPU porting of Smilei advances, LWFA features in progress

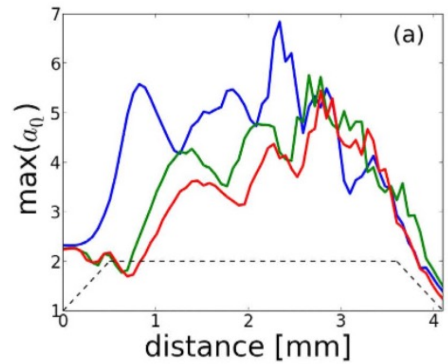
- Quick simulations allow to generate datasets for ML, compare optimization methods

Additional slides

Laser field and LWFA experiment reconstruction: some results in the literature

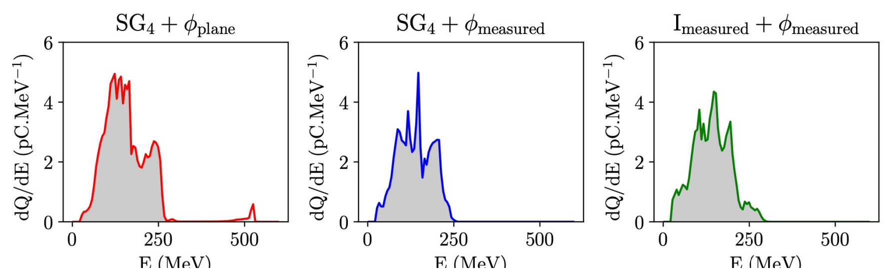


Beaurepaire, B. et al,
Phys. Rev. X **5,** 031012 (2015)

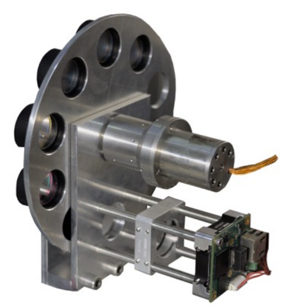


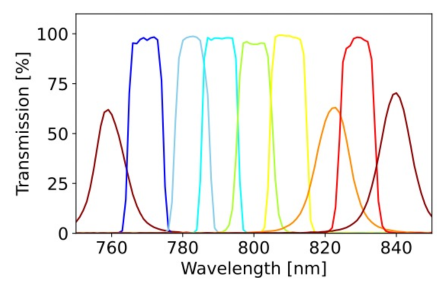
J. Ferri et al,
Sc. Reports 6,27846 (2016)

I. Zemzemi and A. Beck,
arXiv 2304.09020 (2023)



N. Weiße al,
arXiv 2303.01360 (2023)





Smilei) 4th Smilei user & training workshop

8–10 Nov 2023 @ ELI beamlines & CTU Europe/Prague timezone

https://indico.math.cnrs.fr/event/9577/

Envelope ionization model (1)

- ADK ionization rate averaged over optical cycles

(M. Chen et al., J. Comput. Phys. 2013)

- Initialization of electron transverse momenta after ionization

(P. Tomassini et al., Phys. Plasmas 2017)

$$\mathbf{p}_\perp - \mathbf{A}_\perp = \text{const} \longrightarrow \mathbf{p}_\perp = \mathbf{A}_\perp - \mathbf{A}_{\perp, t_{\text{ioniz}}}$$

$$|\mathbf{p}_{\perp,\mathbf{0}}| = \begin{cases} p_{\text{pol},\,0} \leftarrow N(0, \sigma_{p_\perp}) & \text{Linear Polarization} \\ |\tilde{A}|/\sqrt{2} & \text{Circular Polarization} \end{cases}$$

→ C. B. Schroeder et al., Phys. Rev Accel. Beams (2014)

Accurate description in non-relativistic regime (a_0<1)

Envelope ionization model (2)

- ADK ionization rate averaged over optical cycles

(M. Chen et al., J. Comput. Phys. 2013)

- Initialization of electron transverse momenta after ionization

(P. Tomassini et al., Phys. Plasmas 2017)

- Initialisation des impulsions longitudinales des électrons

(F. Massimo et al., Phys. Rev. E 2020)

$$p_x = \frac{|\mathbf{p}_\perp|^2}{2} = \frac{1}{2}|\mathbf{A}_\perp - \mathbf{A}_{\perp,t_{\text{ioniz}}}|^2 \quad \longrightarrow \quad p_{x,0} = \begin{cases} |\tilde{A}|^2/4 + p^2_{\text{pol},0}/2 \\ |\tilde{A}|^2/2 \end{cases}$$

Accurate description
also in relativistic regimes ($a_0>1$)

Envelope ionization model (3)

Laser Pulse:

a_0=2.5 (linear polarization)

λ_0=0.8 μm

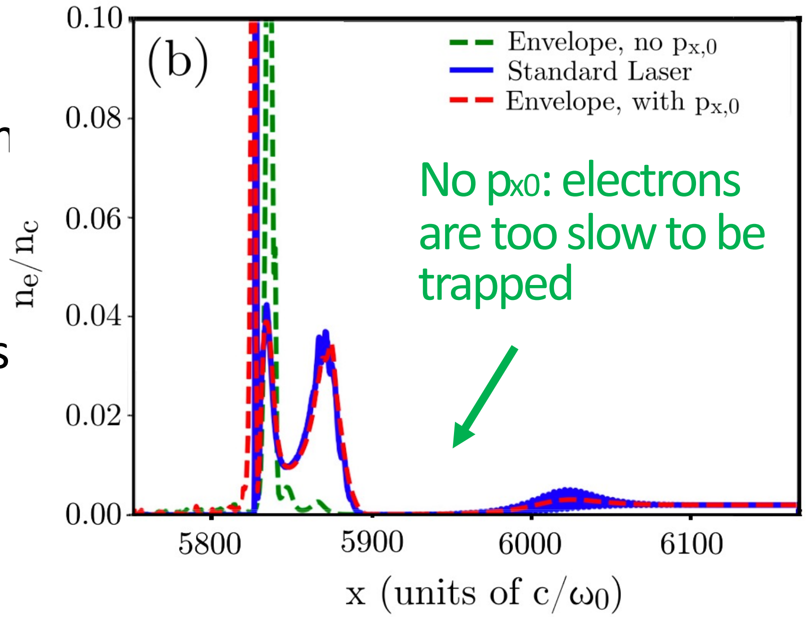
w_0=19 μm

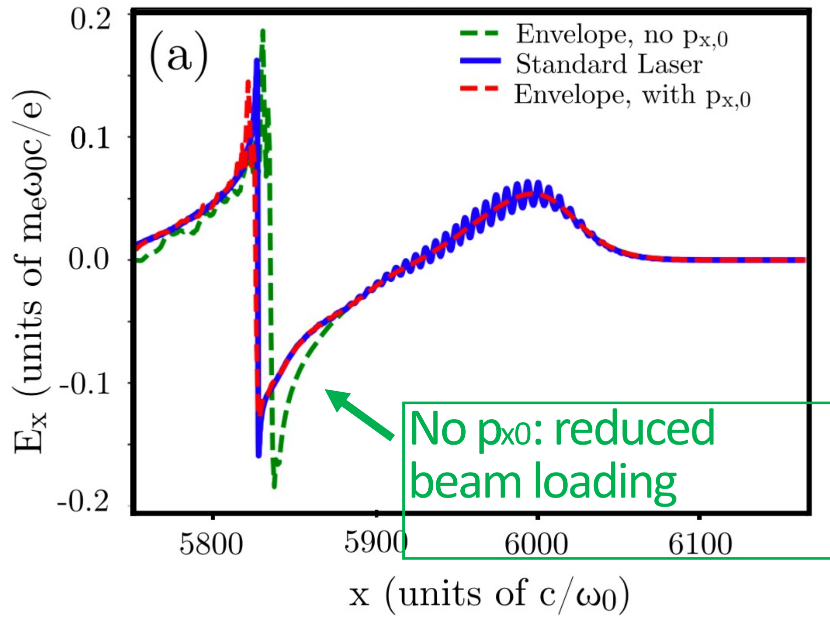
T_{FWHM}=33 fs

Gas target (99%He +1%N^{5+}):

n=3.4*10^{8}cm^{-3}

L=800 μm





F. Massimo et al., Phys. Rev E (2020)