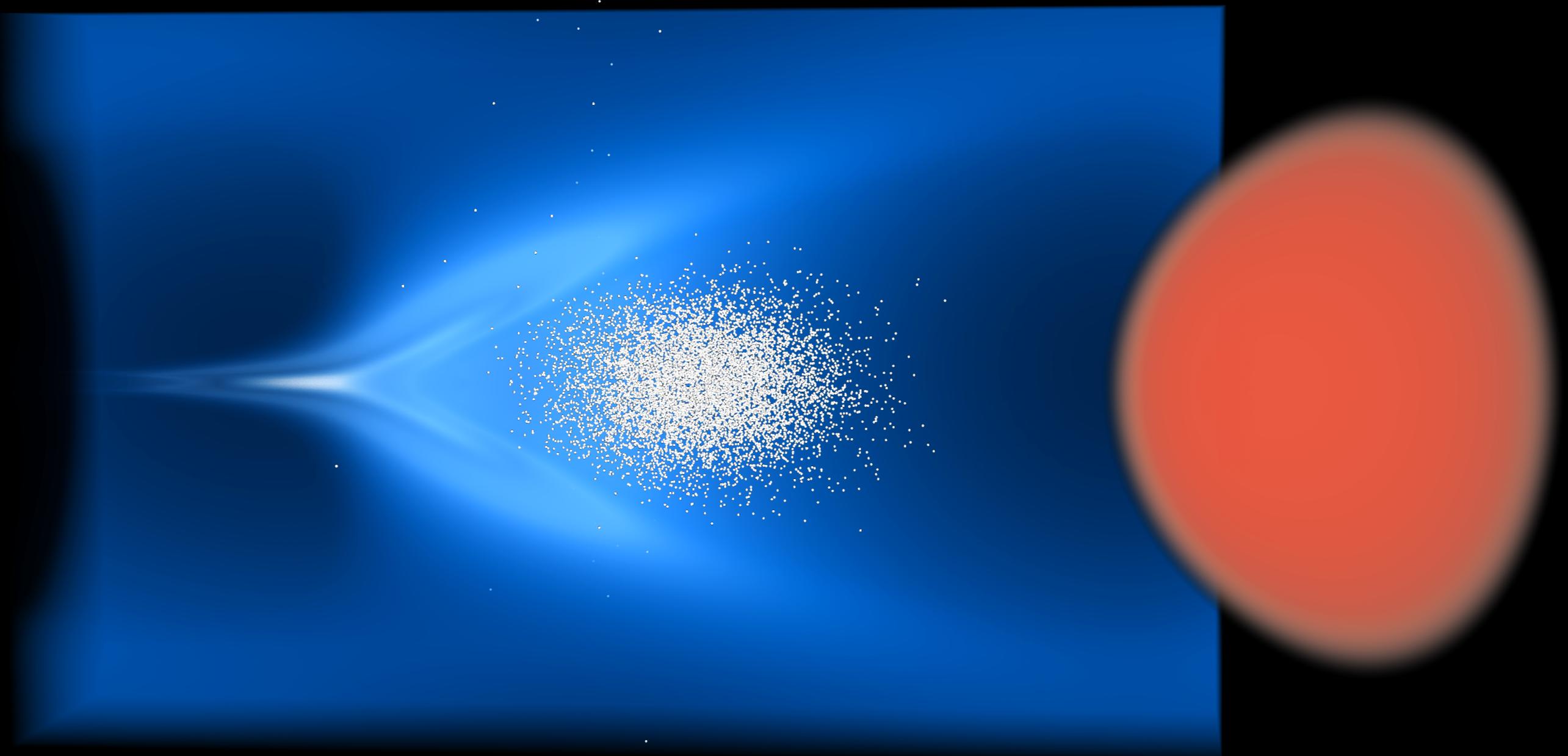


Simulation of Laser Wakefield Acceleration



Francesco Massimo, LPGP

1-4 Dec 2023



Outline

- Why plasma accelerators?
- Basics of plasma acceleration
- Numerical simulation of plasma acceleration: PIC codes
- The PIC code Smilei
- Introduction to the case study and the practical

Outline

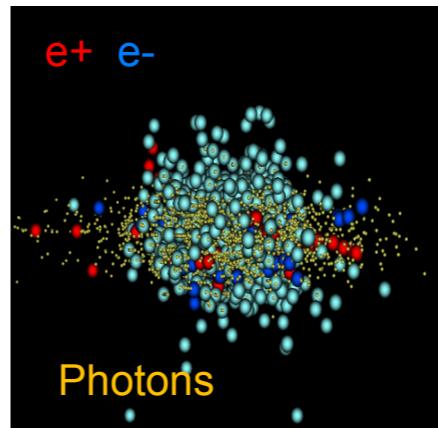
- Why plasma accelerators?
- Basics of plasma acceleration
- Numerical simulation of plasma acceleration: PIC codes
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Applications of high energy electrons (just a few)

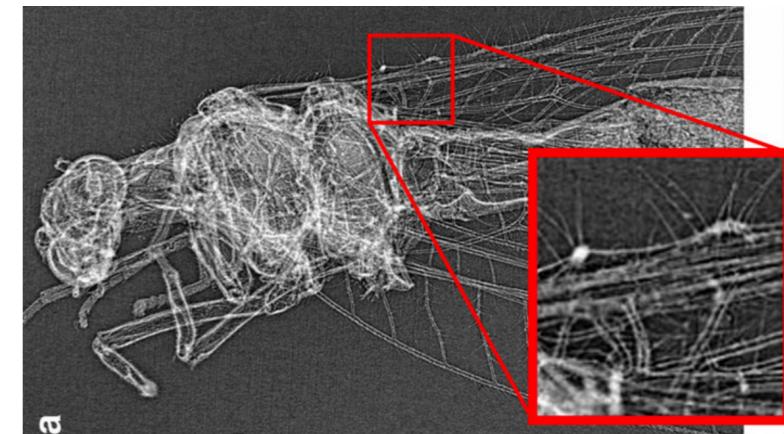
Fundamental Research:

- QED, Particle physics
- Matter Physics
- Biology

Smilei Simulation
of QED e^+e^- pairs creation
from photons



J. Wenz et al., Nat Comm 2014
Imaging through Betatron radiation

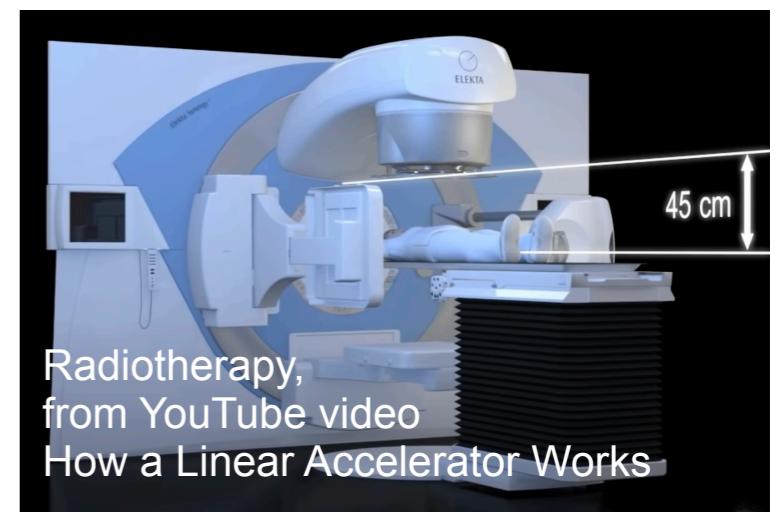


Medicine, Industry, Heritage, ...:

- Cancer treatment,
- Medical imaging
- Electronic industry
- Study of materials
- Authentication of artwork
- ...



Hidden Archimede's Palimpsest,
revealed by SLAC's synchrotron radiation
in 2005 (U. Bergmann)



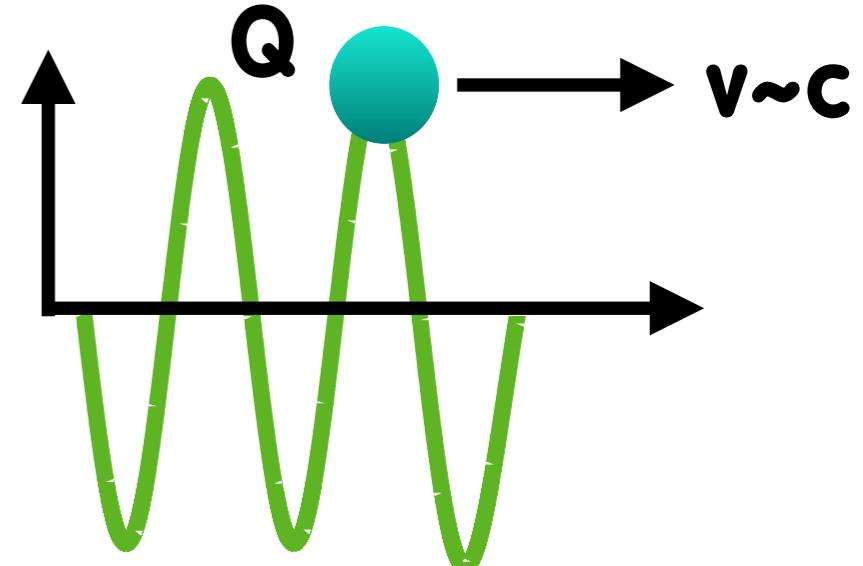
Particle accelerators size and cost

Relativistic charge **Q**

In an accelerating cavity of length **L**

With peak accelerating field **E**

**Electric
Field**



$$\text{Maximum energy gain} = Q E L$$

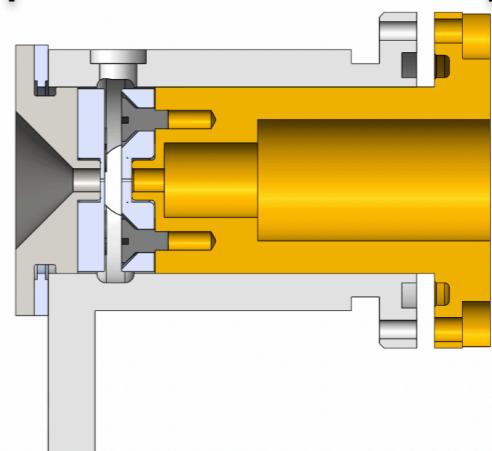
Given a target energy,

if **E** is limited by technology, **L** increases

→ need more metallic cavities

→ the accelerator size and cost increase

Particle accelerators size and cost

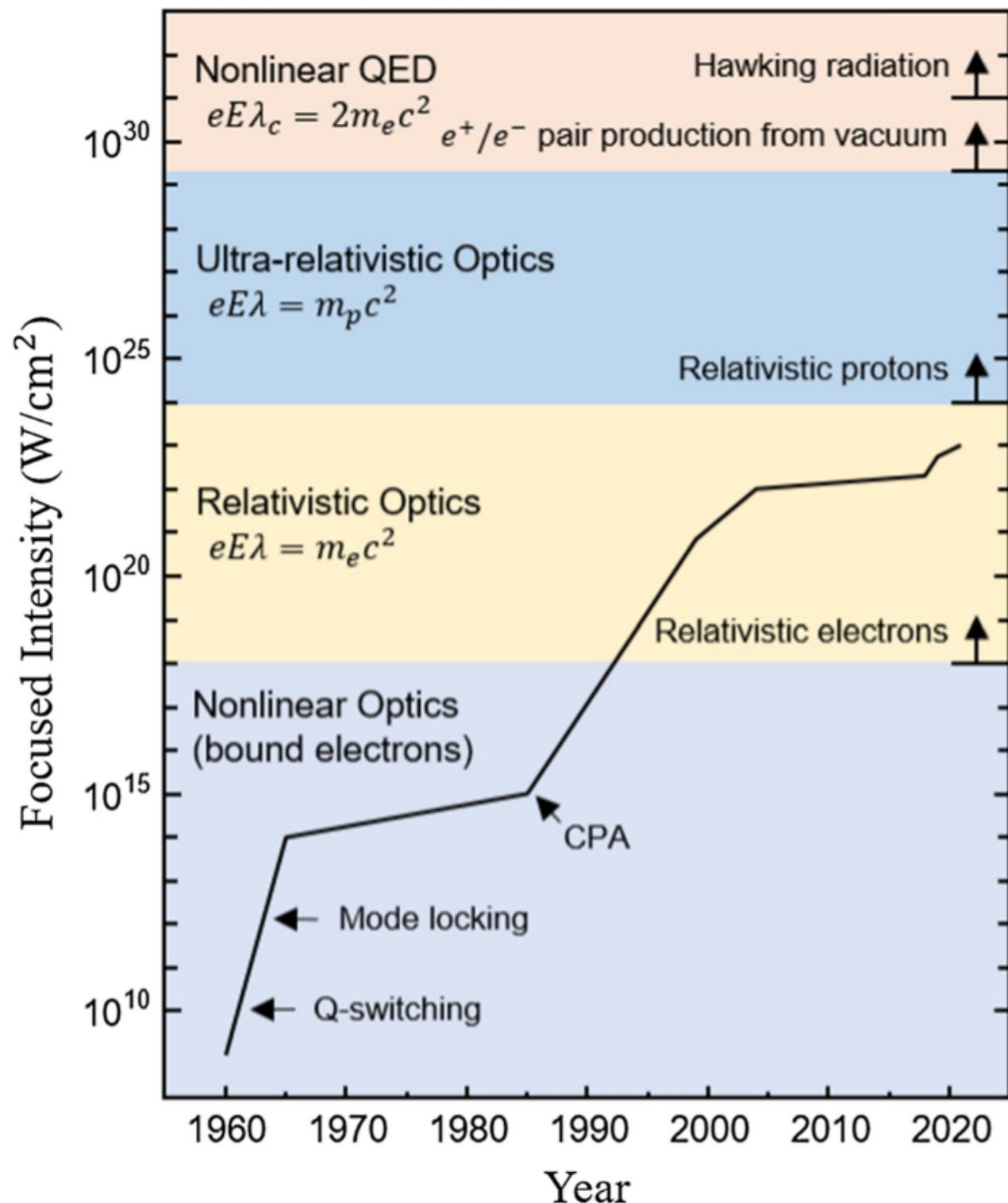
Accelerator technology	Peak Accelerating Field	Acceleration length to gain 100 MeV	~1 m H Accelerating Cavity
Radiofrequency metallic cavities	$\sim 10^2$ MV/m	1 m	
Laser Wakefield Acceleration (LWFA)*	$\sim 10^4$ MV/m	0.01 mm	 ~ 1 mm

***Open challenge: improve performances
of Laser Wakefield Acceleration.
Numerical modeling is necessary!**

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High Intensity Lasers and their interaction with matter



Techniques:

- Chirped Pulse Amplification
- Femtosecond Lasers
- Nonlinear Optics
- ...

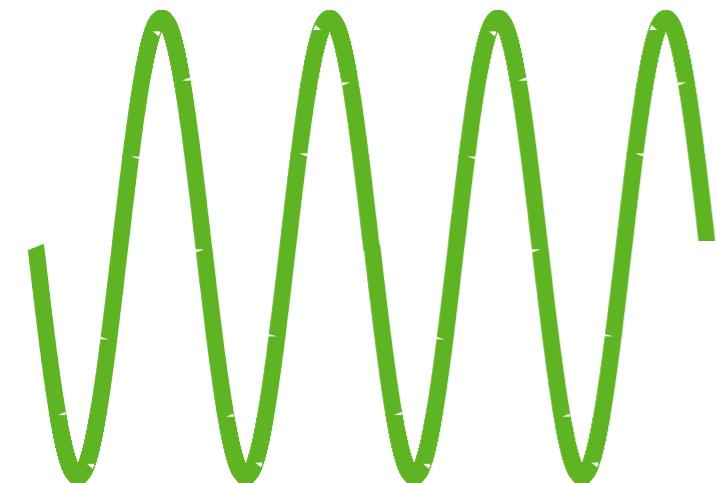
Physics Domains:

- Relativistic Fluids
- Physics of Relativistic Plasmas
- Relativistic Optics
- Laboratory Astrophysics

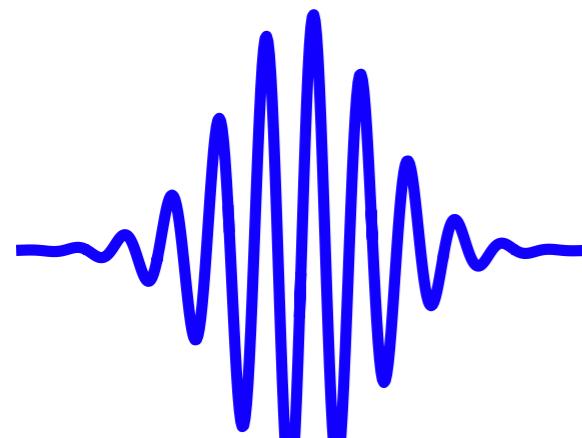
Applications:

- Electron and ion sources
- Acceleration of particles
- Radiation sources (UV, X, γ)
- Novel, high resolution diagnostics
- Pump-probe measurements

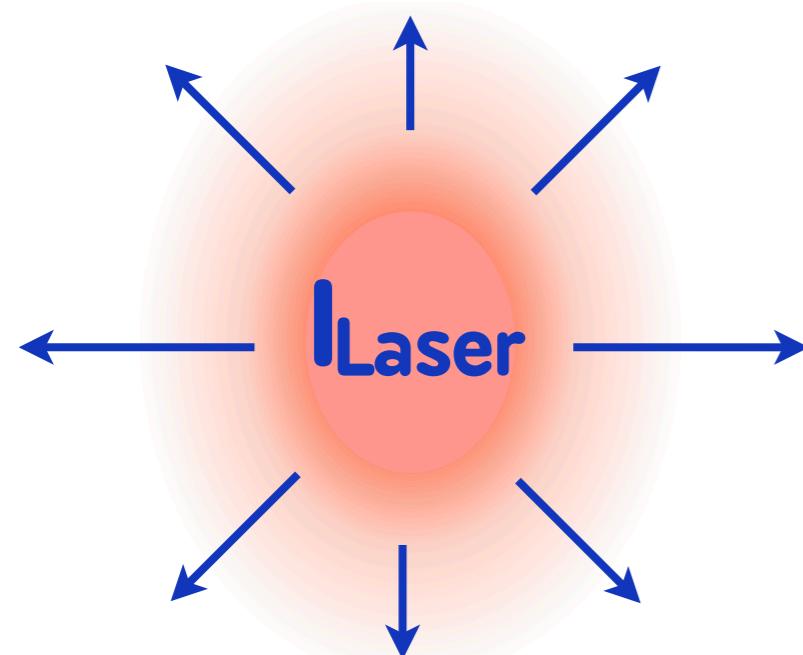
Ponderomotive Force: the trigger for laser wakefield excitation in plasmas



Electron in infinite plane wave:
Oscillating Force



Electron in finite laser pulse:
Oscillating Force + Ponderomotive Force



$$F_{\text{pond}} \propto -\nabla I_{\text{Laser}} \quad (\text{a.k.a. radiation pressure})$$

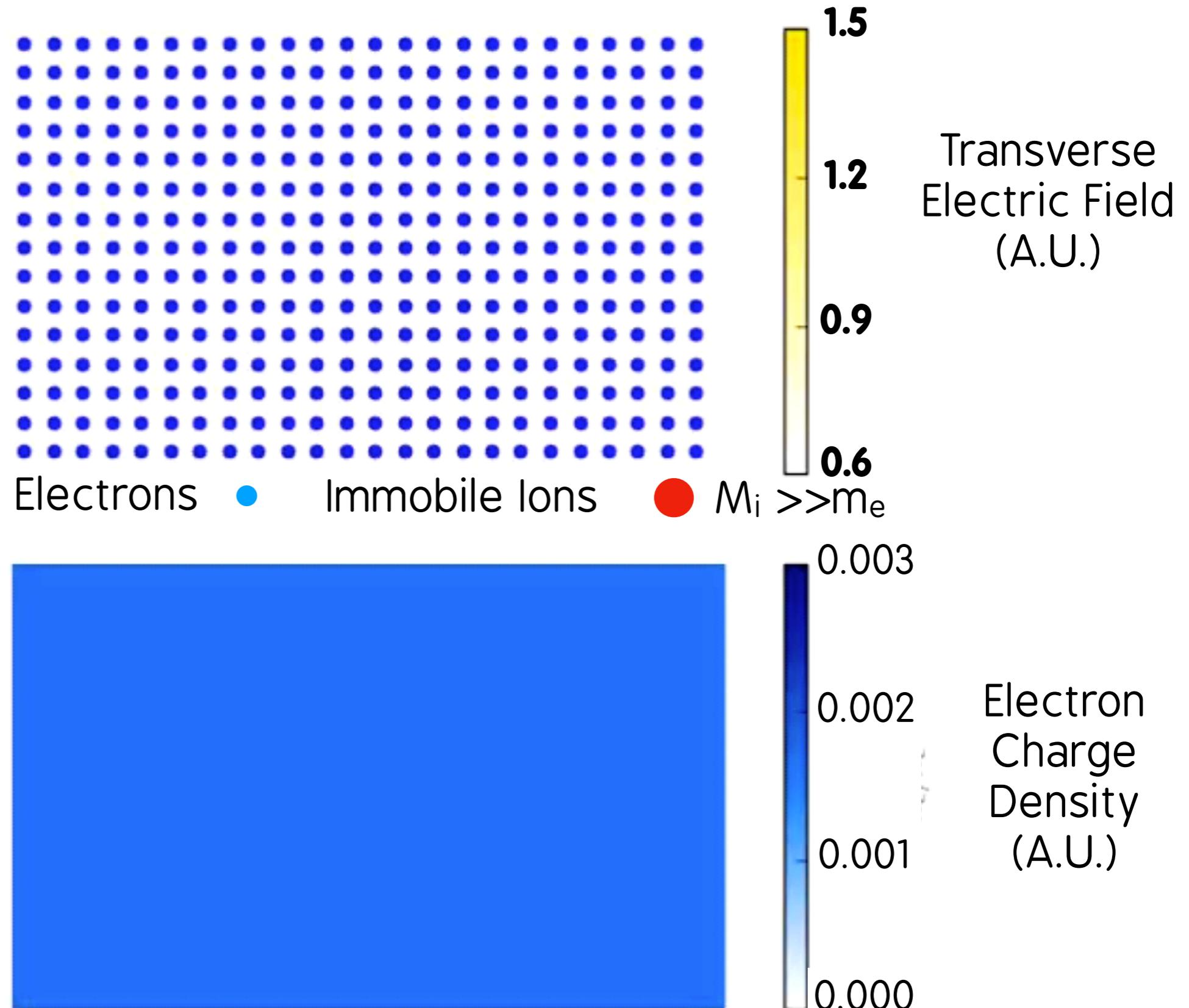
Laser Wakefield Acceleration (LWFA): plasma wave excitation by the laser ponderomotive force

Laser Beam
Duration: 28 fs

Ponderomotive
Force:
 $F = -\nabla I_{\text{Laser}}$

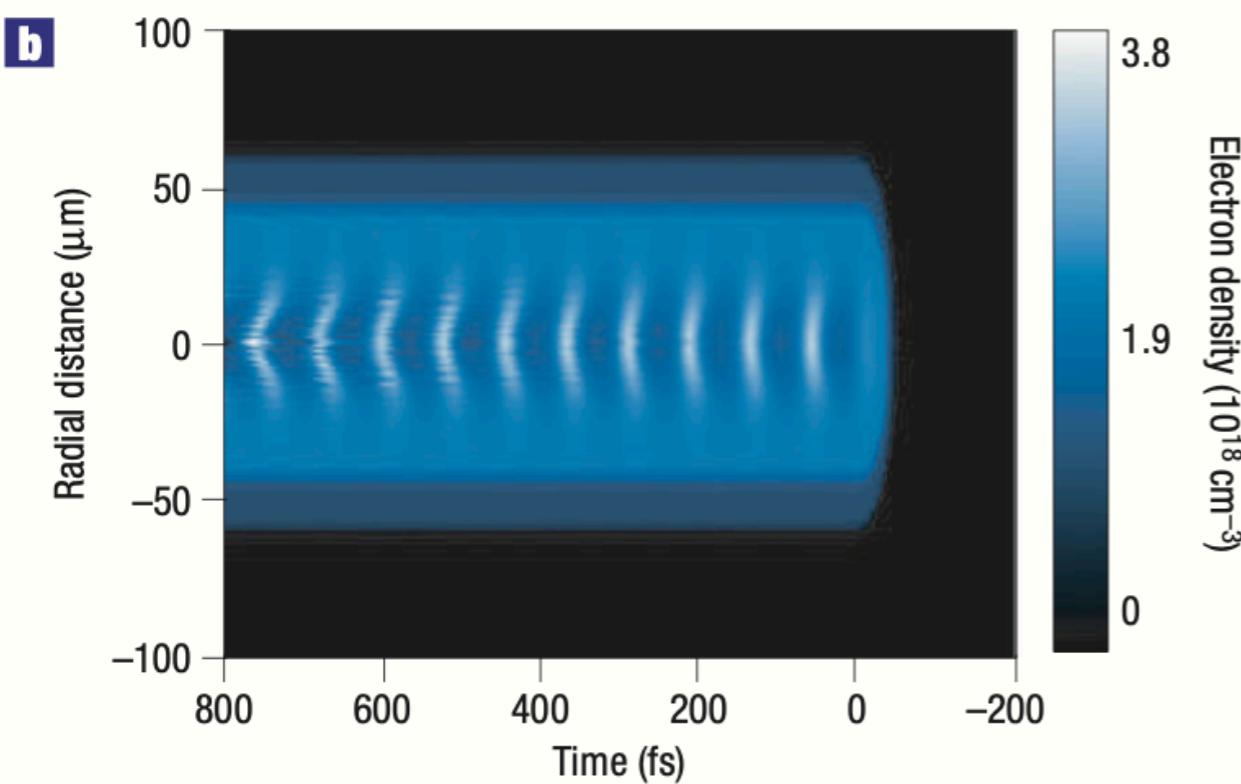
Plasma density:
 $3 \cdot 10^{18} \text{ cm}^{-3}$

Plasma
wavelength:
 $\sim 20 \mu\text{m}$

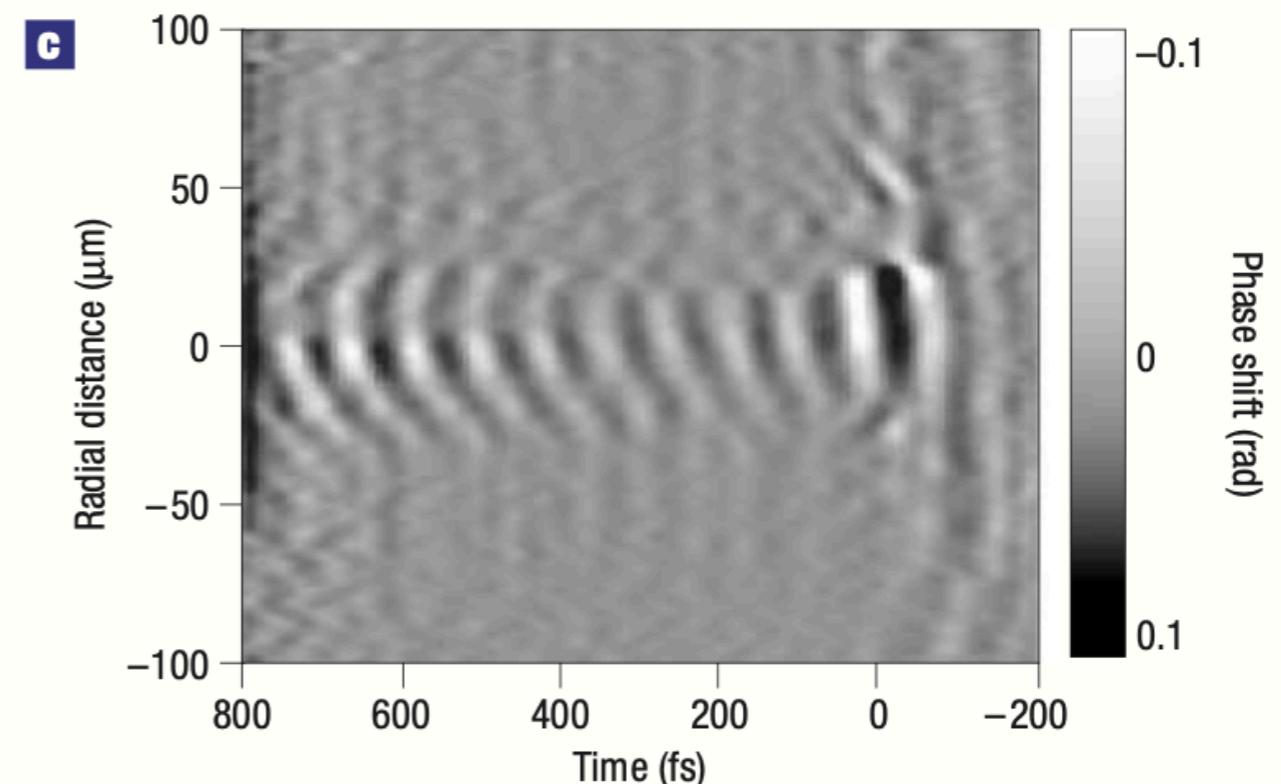


Laser Wakefield Acceleration (LWFA): visualising the plasma waves

Simulation



Experiment

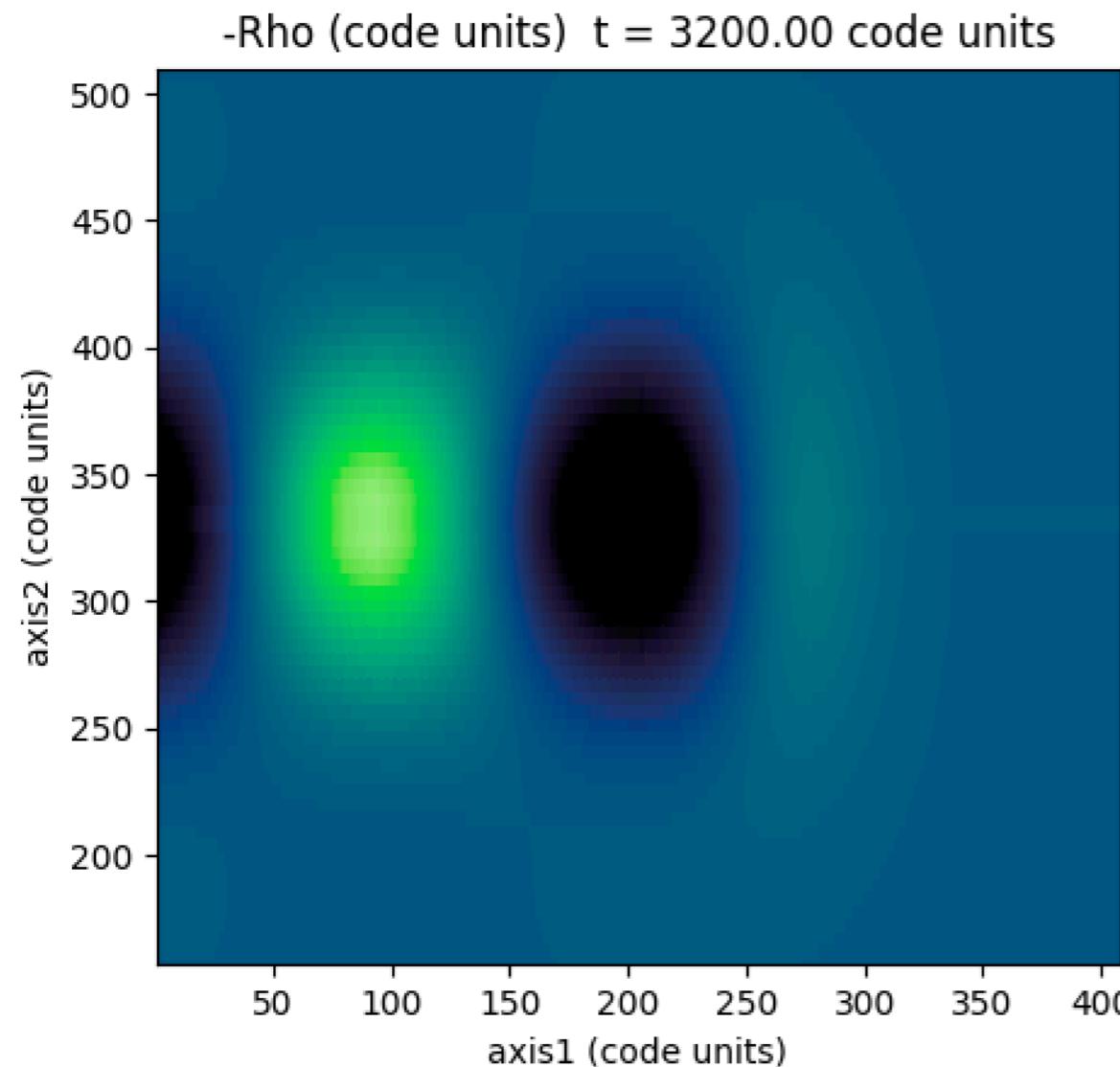


N. Matlis et al., Snapshots of laser wakefields, Nature Physics (2006)

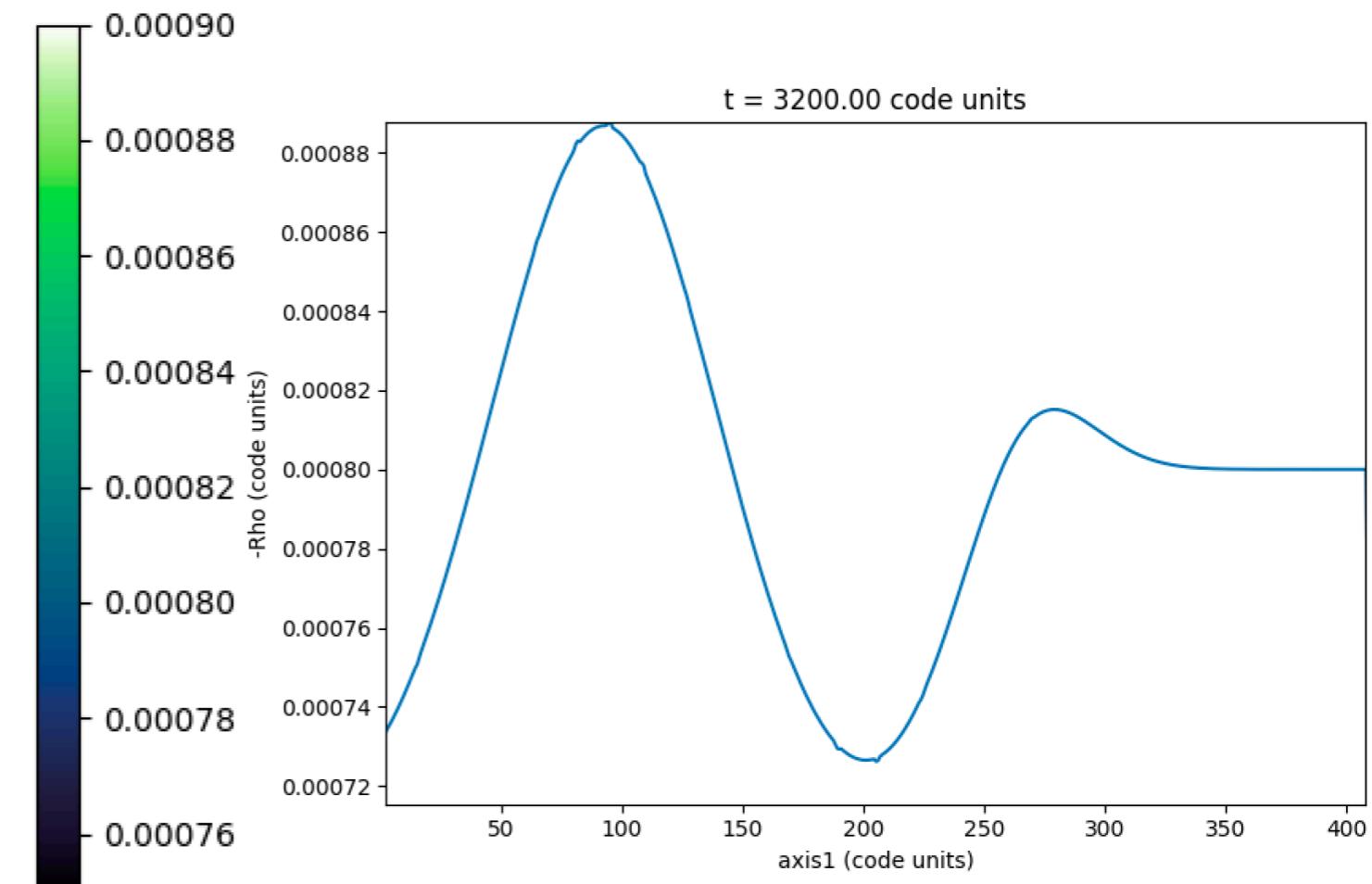
Laser wakefield excitation: linear regime

a_0 = normalized laser peak field = $0.86 \lambda_0[\mu\text{m}] (I [10^{18} \text{W/cm}^2])^{1/2}$

$a_0 \ll 1$: Linear regime
Sinusoidal plasma waves at the plasma frequency



2D charge density

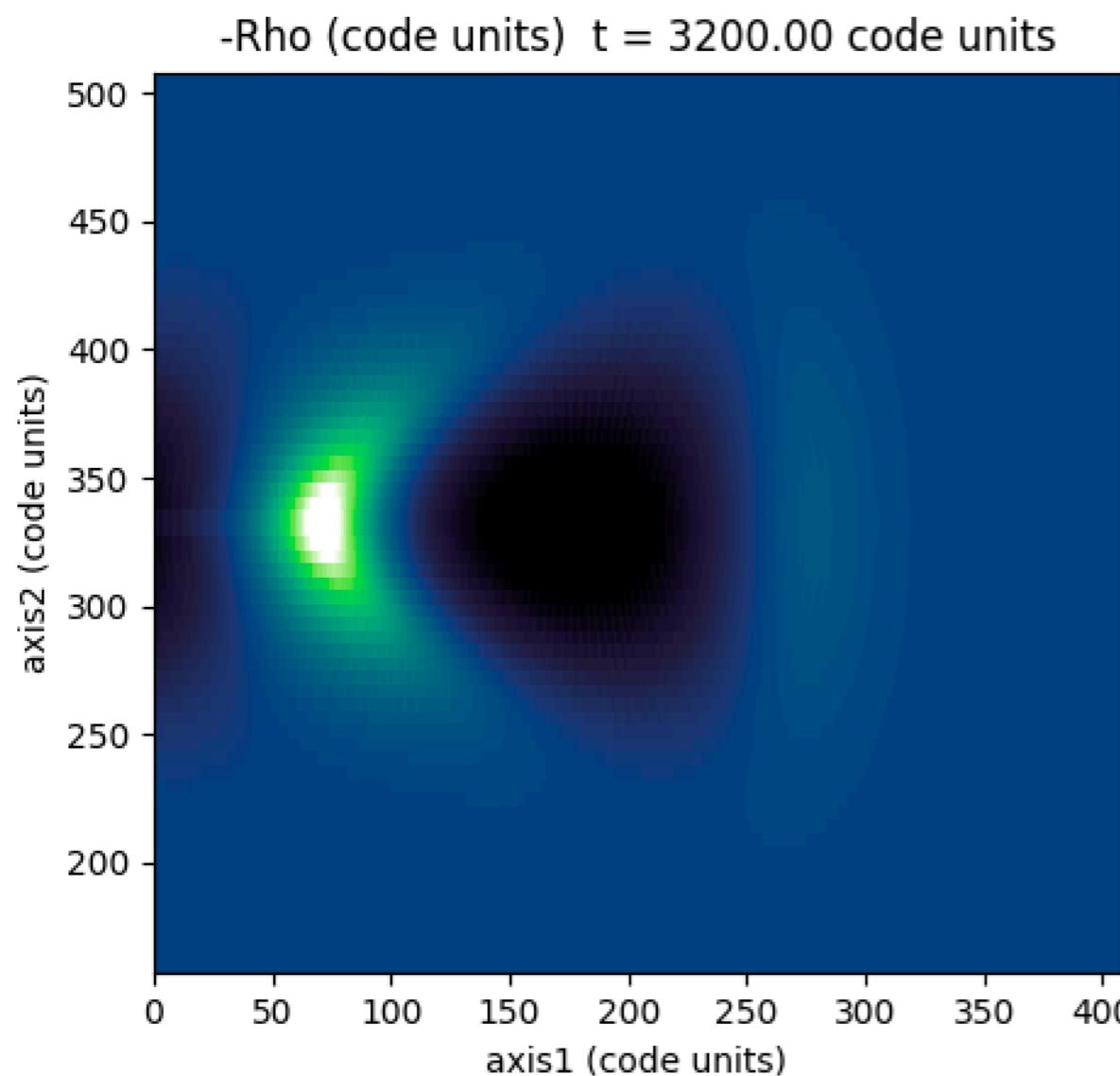


1D charge density
on propagation axis

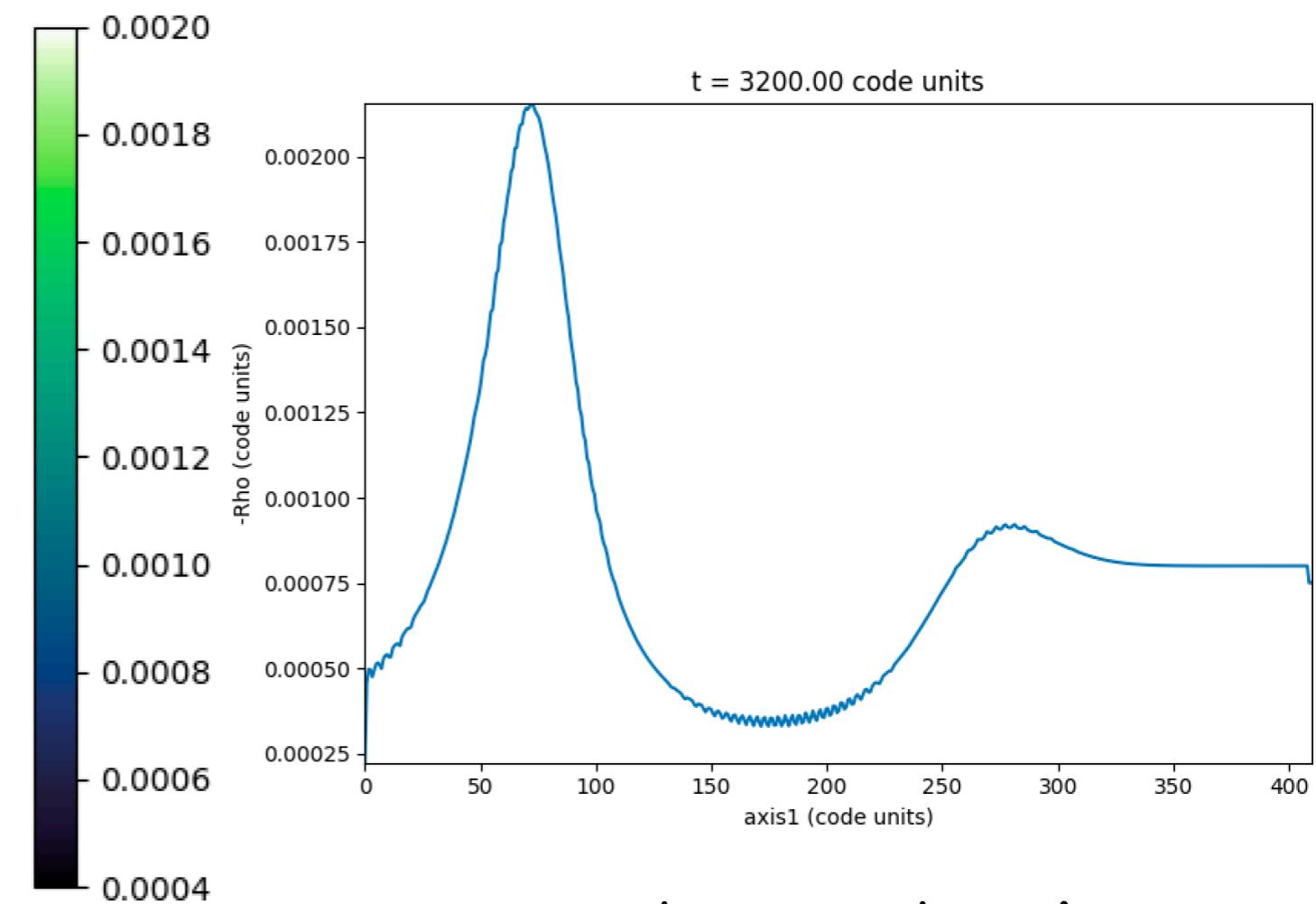
Laser wakefield excitation: weakly linear regime

a_0 = normalized laser peak field = $0.86 \lambda_0[\mu\text{m}] (I [10^{18} \text{W/cm}^2])^{1/2}$

$a_0 \lesssim 1$: Weakly nonlinear regime



2D charge density

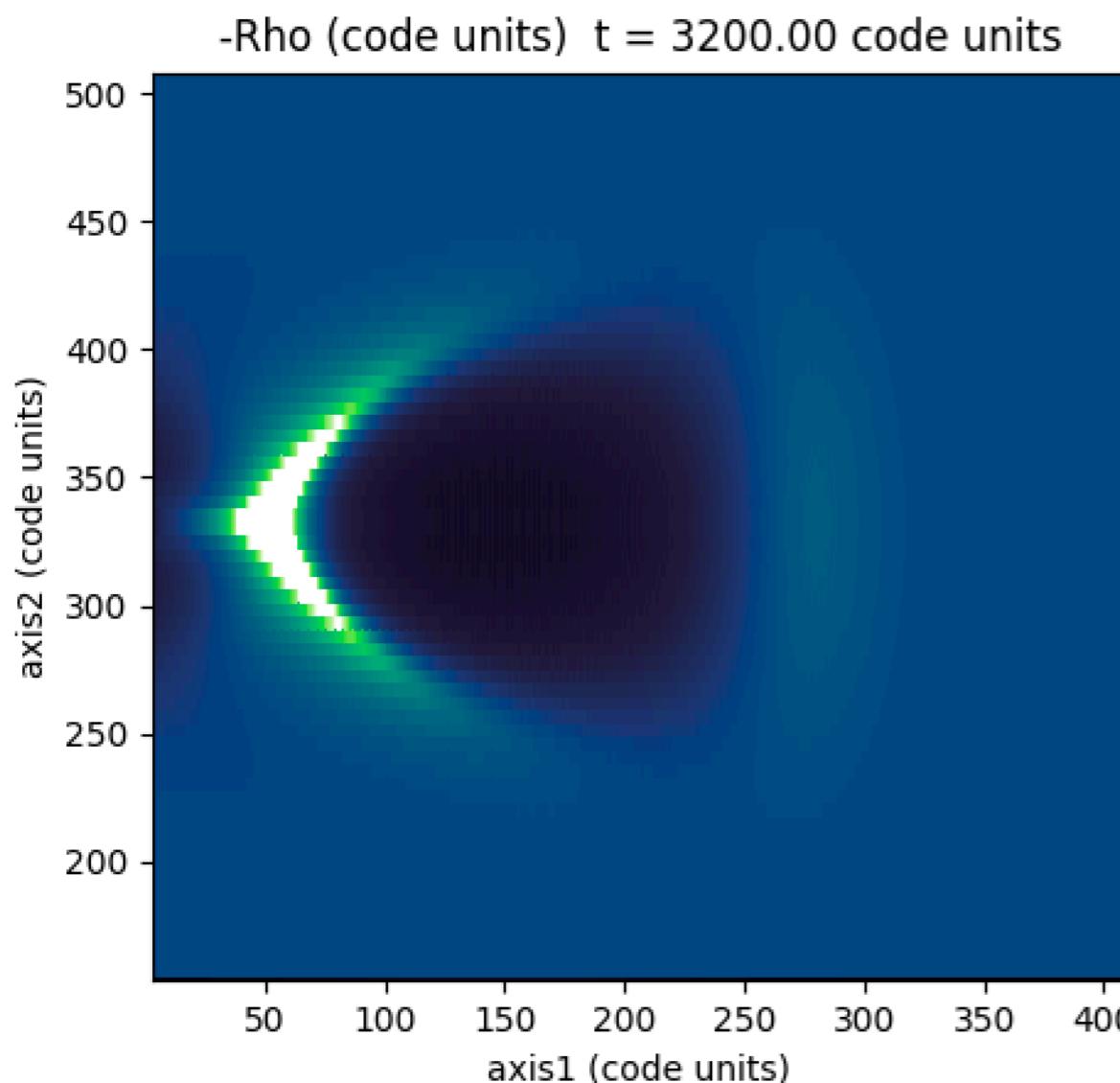


1D charge density
on propagation axis

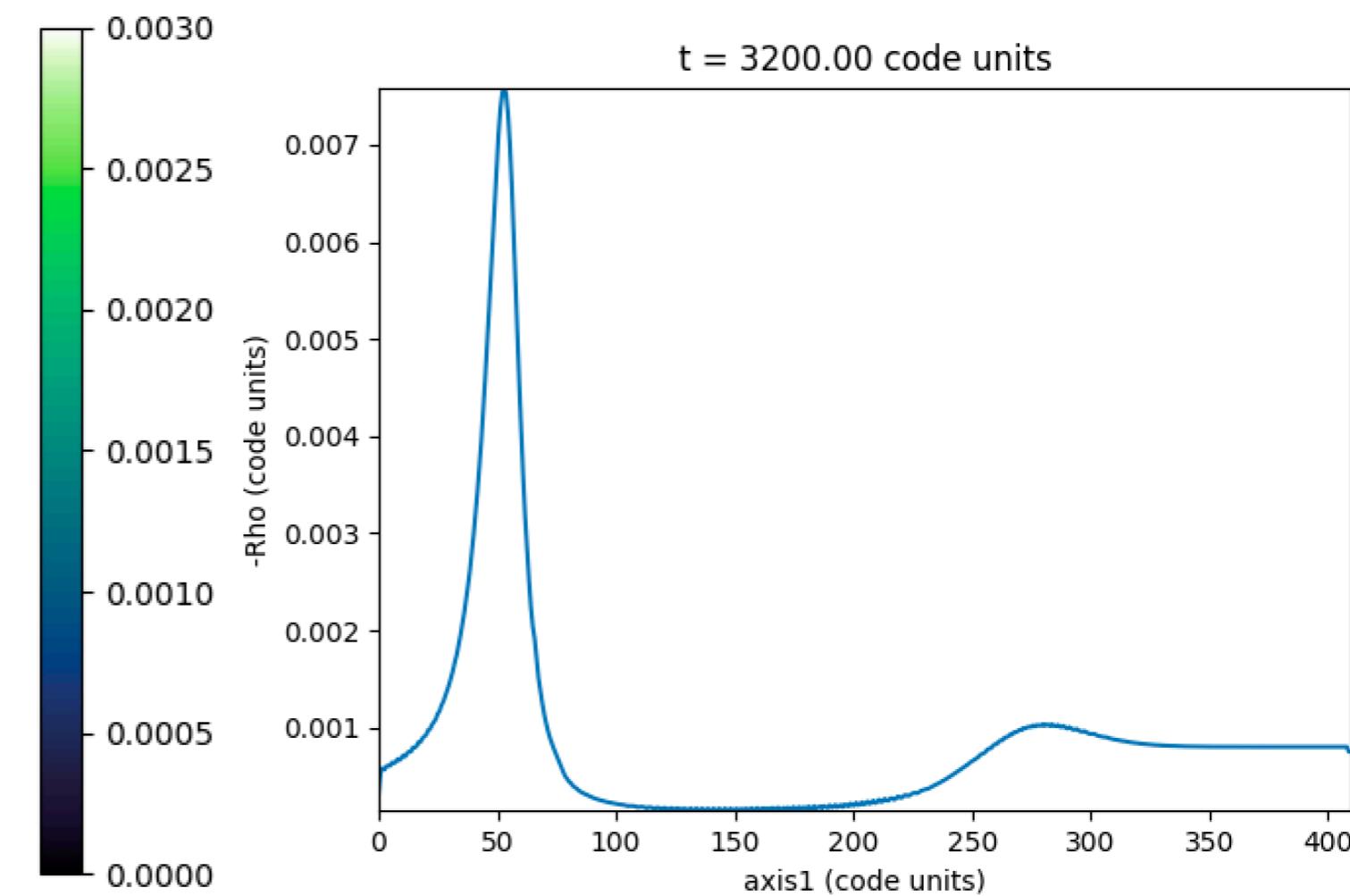
Laser wakefield excitation: nonlinear regime

a_0 = normalized laser peak field = $0.86 \lambda_0[\mu\text{m}] (I [10^{18} \text{W/cm}^2])^{1/2}$

**$a_0 > 1$: Nonlinear regime
“Bubble”-like waves**



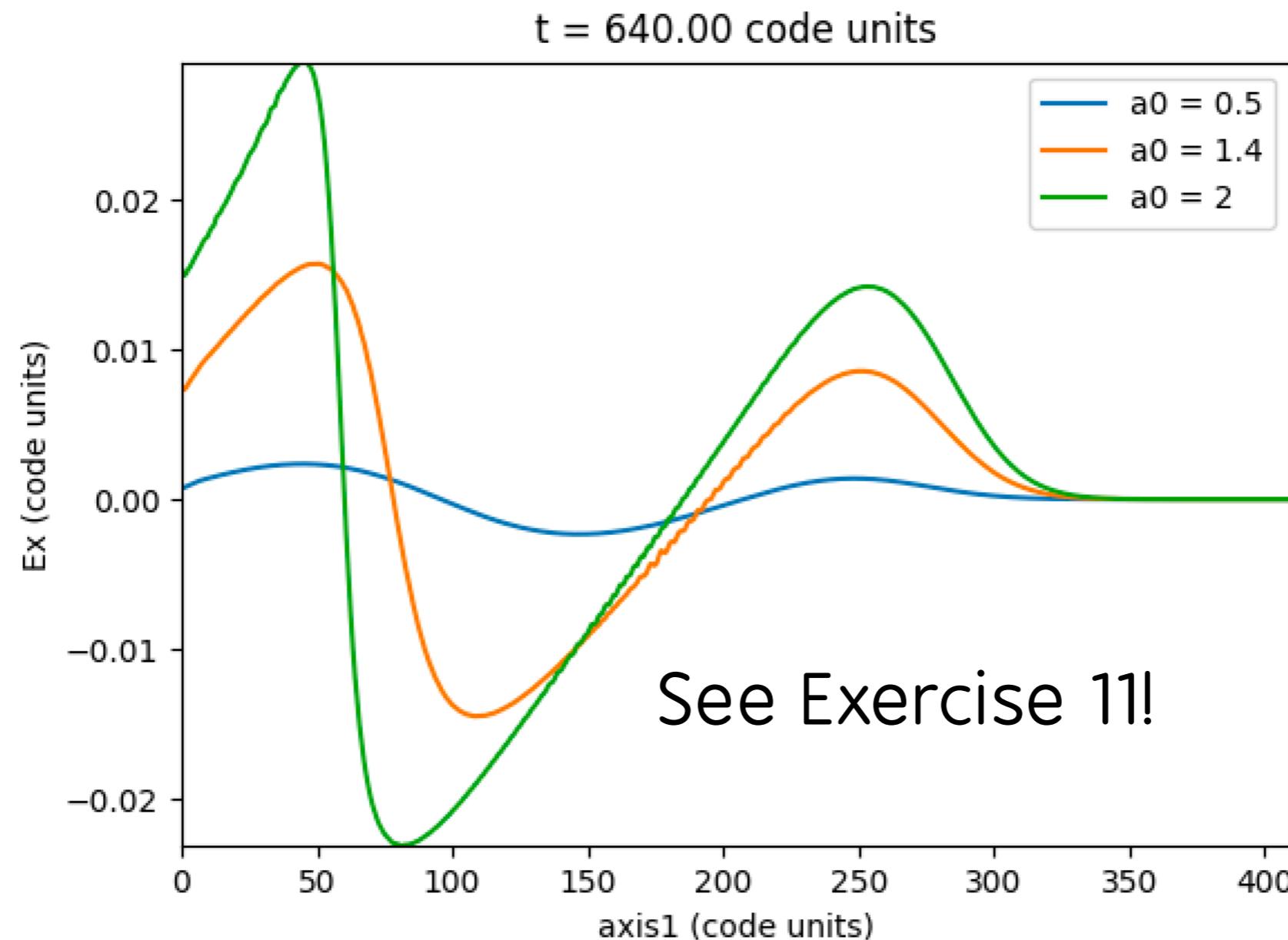
2D charge density



1D charge density
on propagation axis

Laser wakefield excitation regimes: Ex on axis

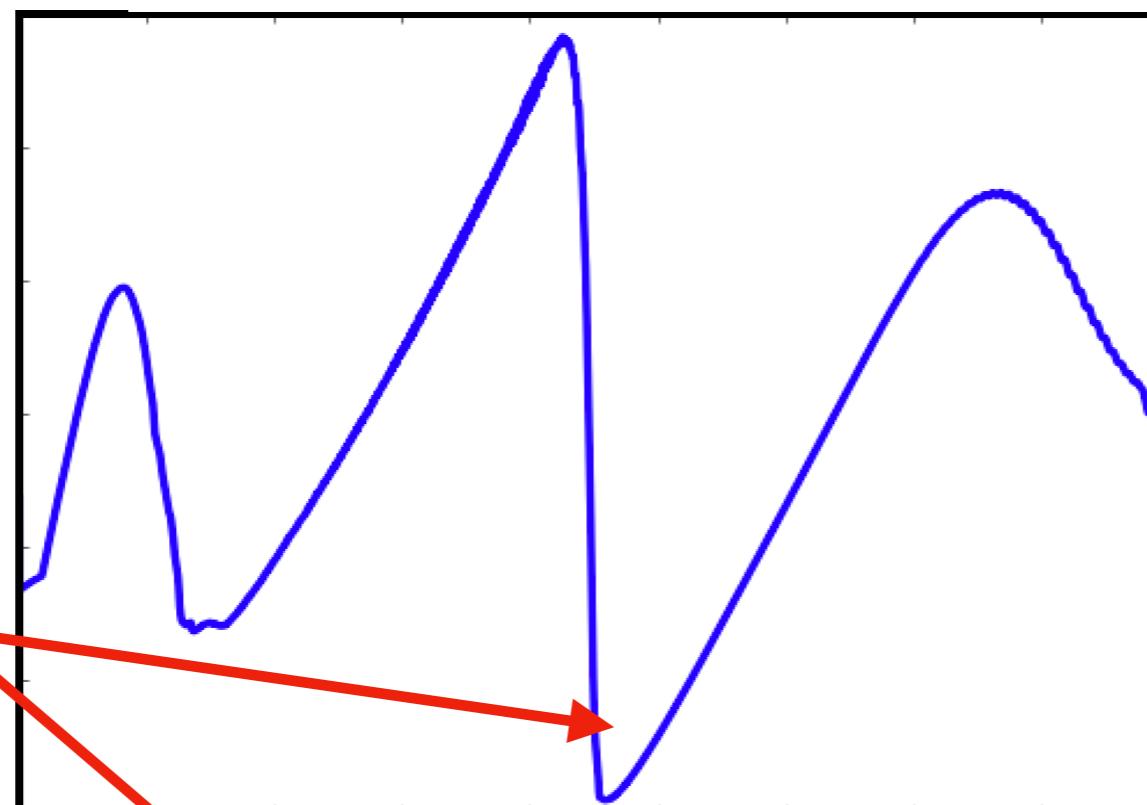
```
import happy
S1 = happy.Open("path/to/sim1"); Ex1 = S1.Probe.Probe0("Ex",timesteps=1000)
S2 = happy.Open("path/to/sim2"); Ex2 = S2.Probe.Probe0("Ex",timesteps=1000)
S3 = happy.Open("path/to/sim3"); Ex3 = S3.Probe.Probe0("Ex",timesteps=1000)
happy.multiPlot(Ex1,Ex2,Ex3,figure=3)
```



Laser Wakefield Acceleration (LWFA): accelerating electric field

$E > 100 \text{ GV/m}$

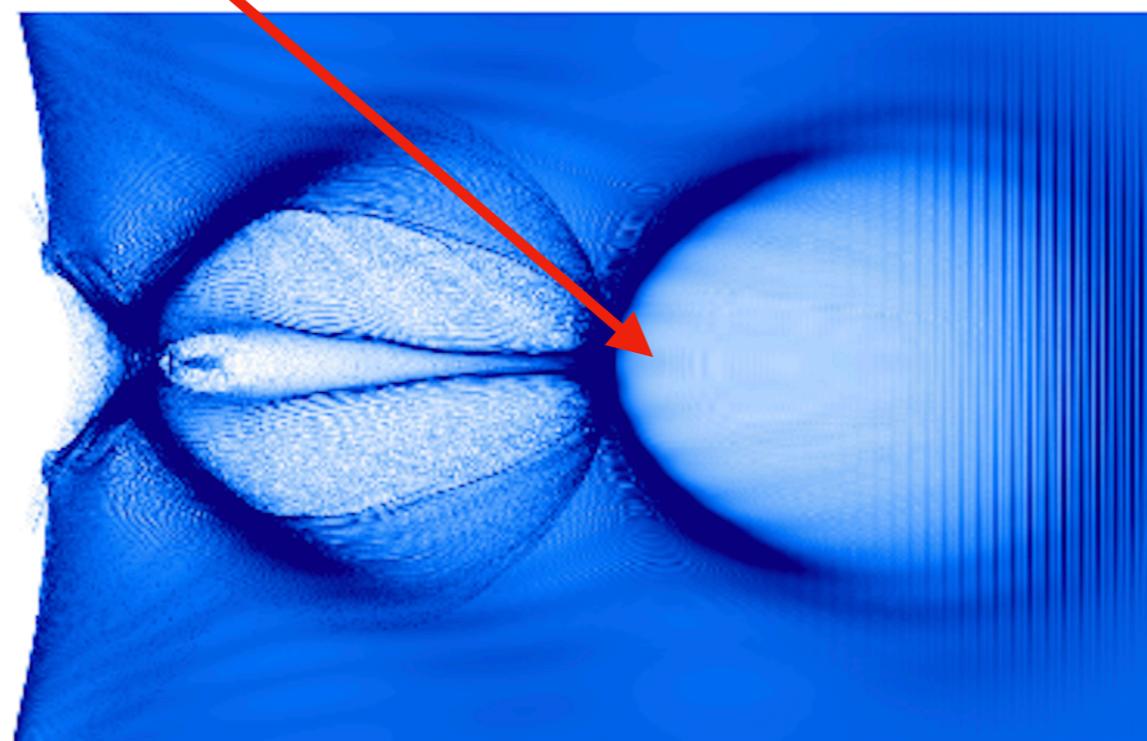
Relativistic electrons injected here are accelerated towards the right



0.04
0.00
-0.04

Longitudinal Electric Field (A.U.)
on propagation axis

Nonlinear regime here

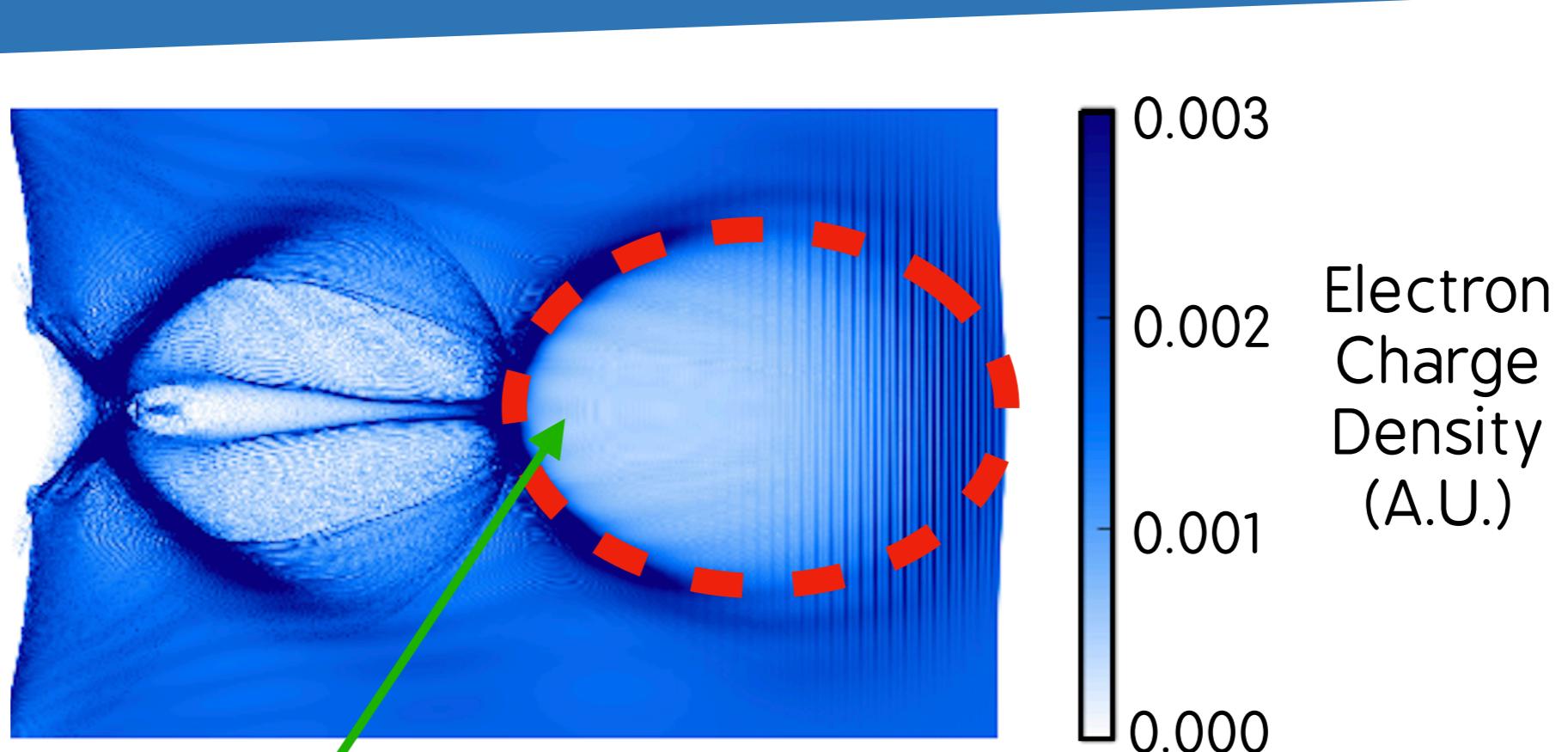


0.003
0.002
0.001
0.000

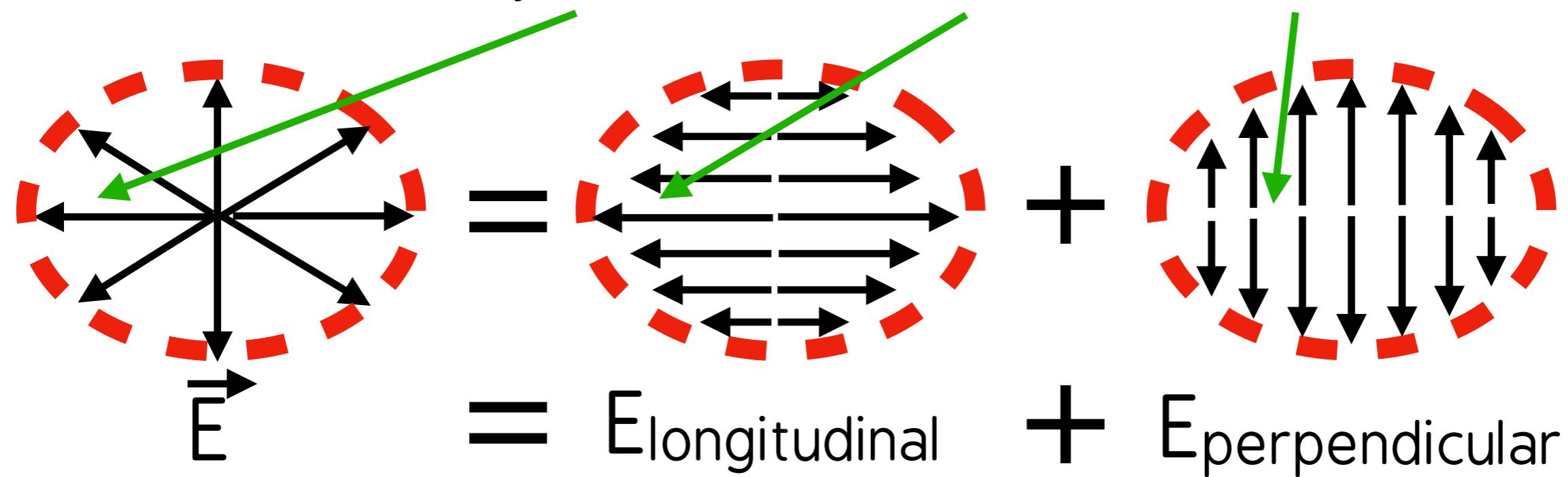
Electron Charge Density (A.U.)

LWFA: Electric fields inside the “bubble”

Plasma wavelength:
~20 μm

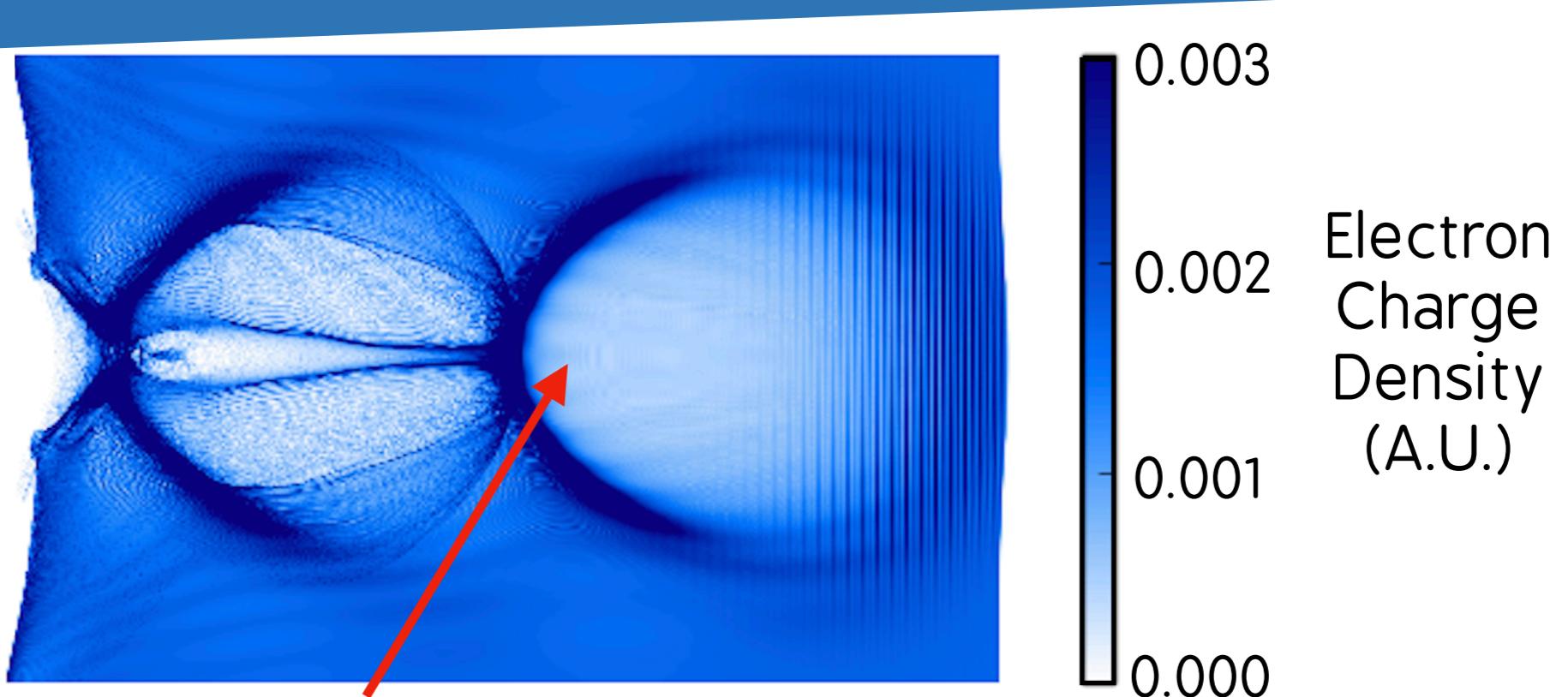


Relativistic electrons injected here are both accelerated and focused

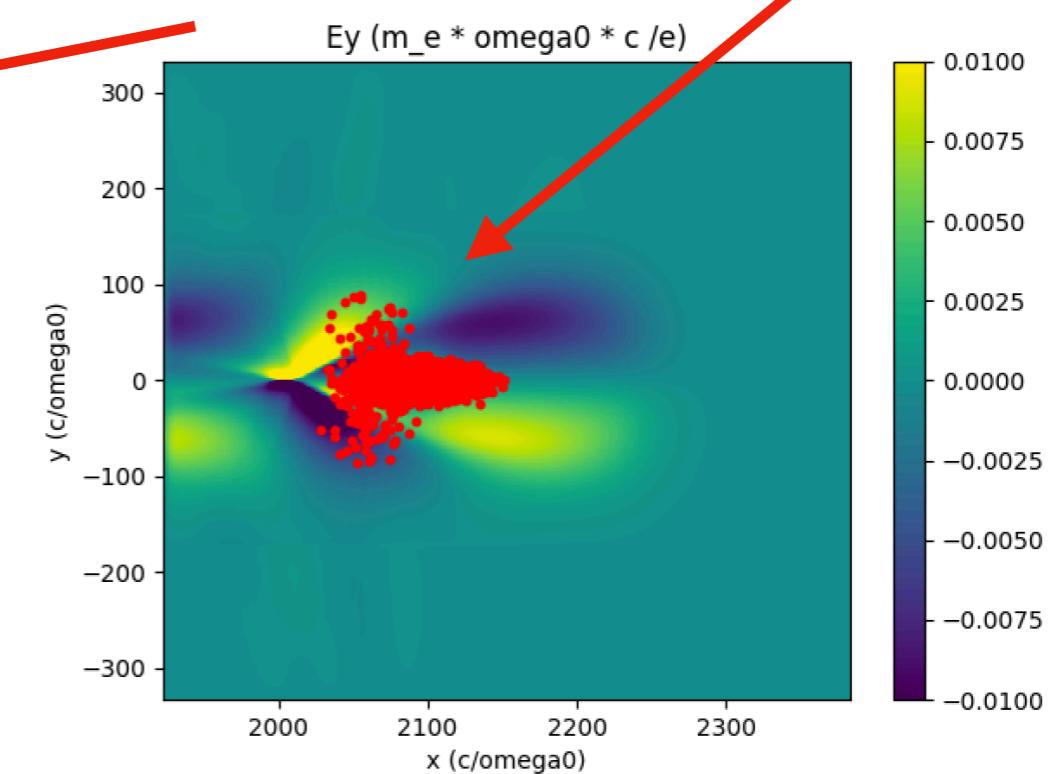
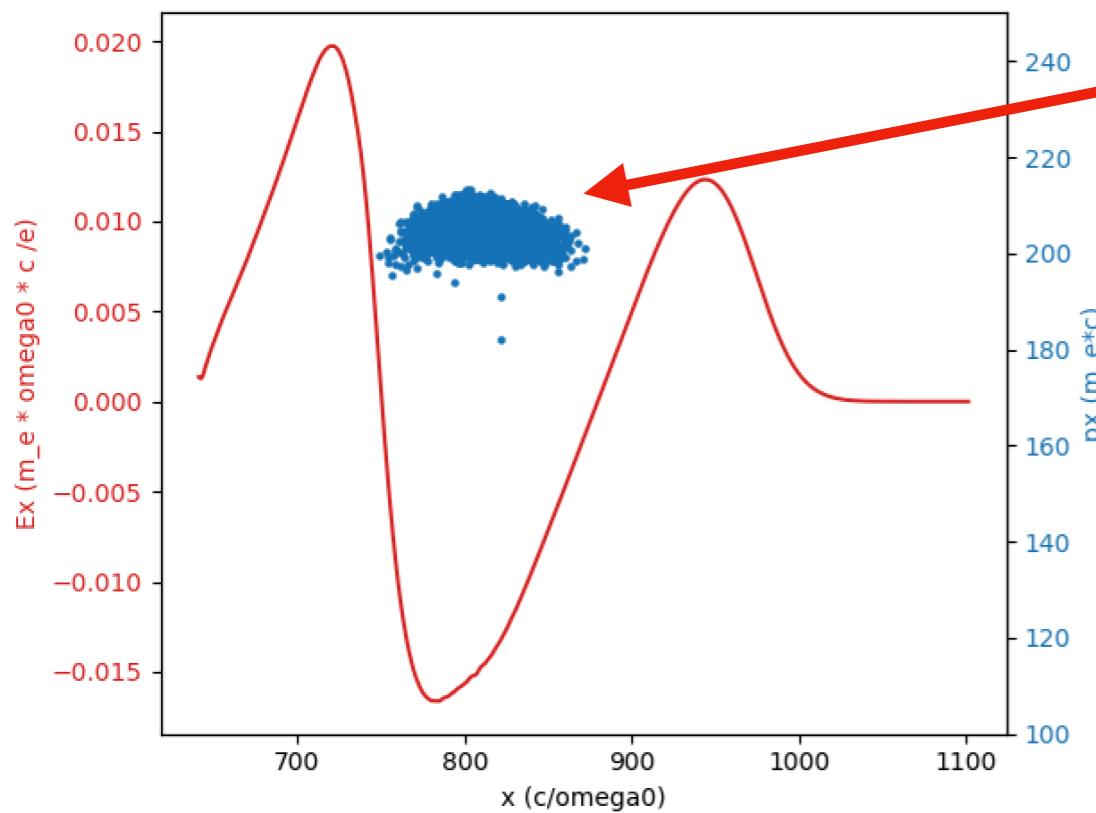


Fields inside the “bubble”: effects on an electron beam

Plasma wavelength:
 $\sim 20 \mu\text{m}$



Relativistic electrons injected **here** are both **accelerated** and **focused**

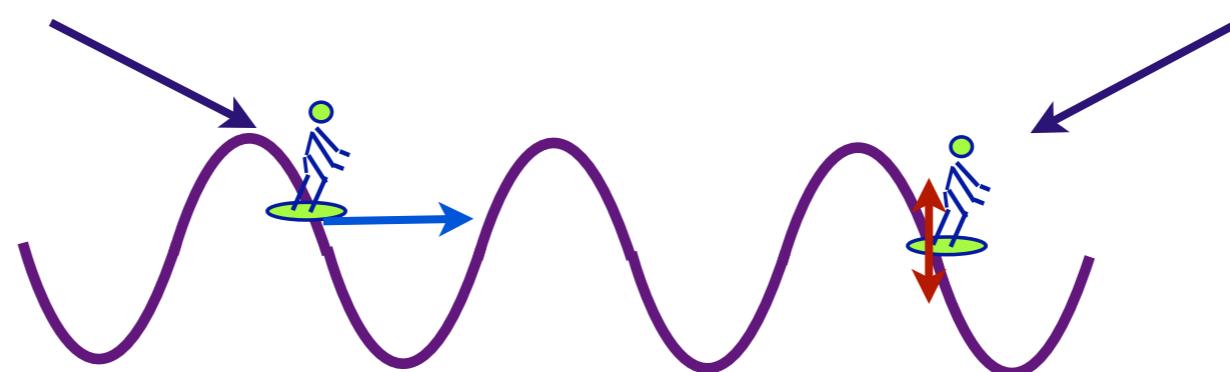


Laser Wakefield Acceleration (LWFA) challenges: injection

Surfer with

- sufficient initial speed,
- injected in the proper phase

Surfer with Zero initial speed



Surfer: electron

wave: electric field of the plasma wave in the wake of the laser

Plasma wavelength $< 100 \mu\text{m}$, Duration of the electron beam $< 10 \text{ fs} \sim 3 \mu\text{m}$

Laser Wakefield Acceleration with ionization injection

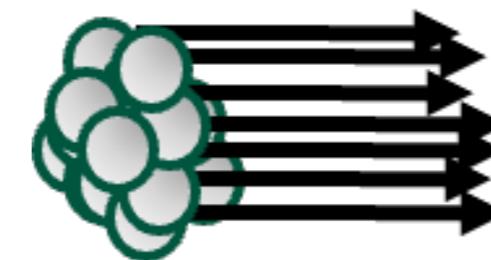
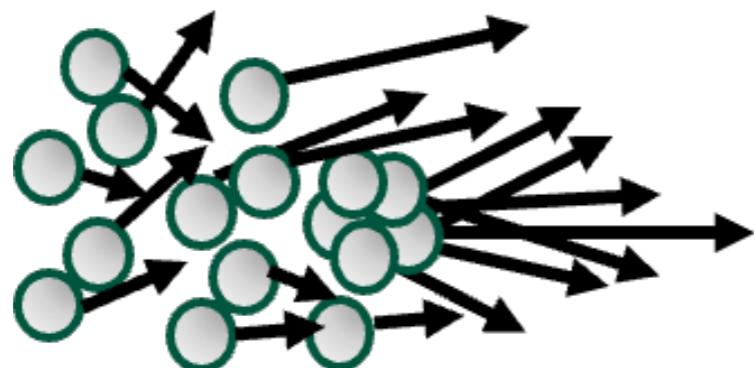


Smilei[®]



Plasma wave
Intense Laser Pulse
High energy electrons

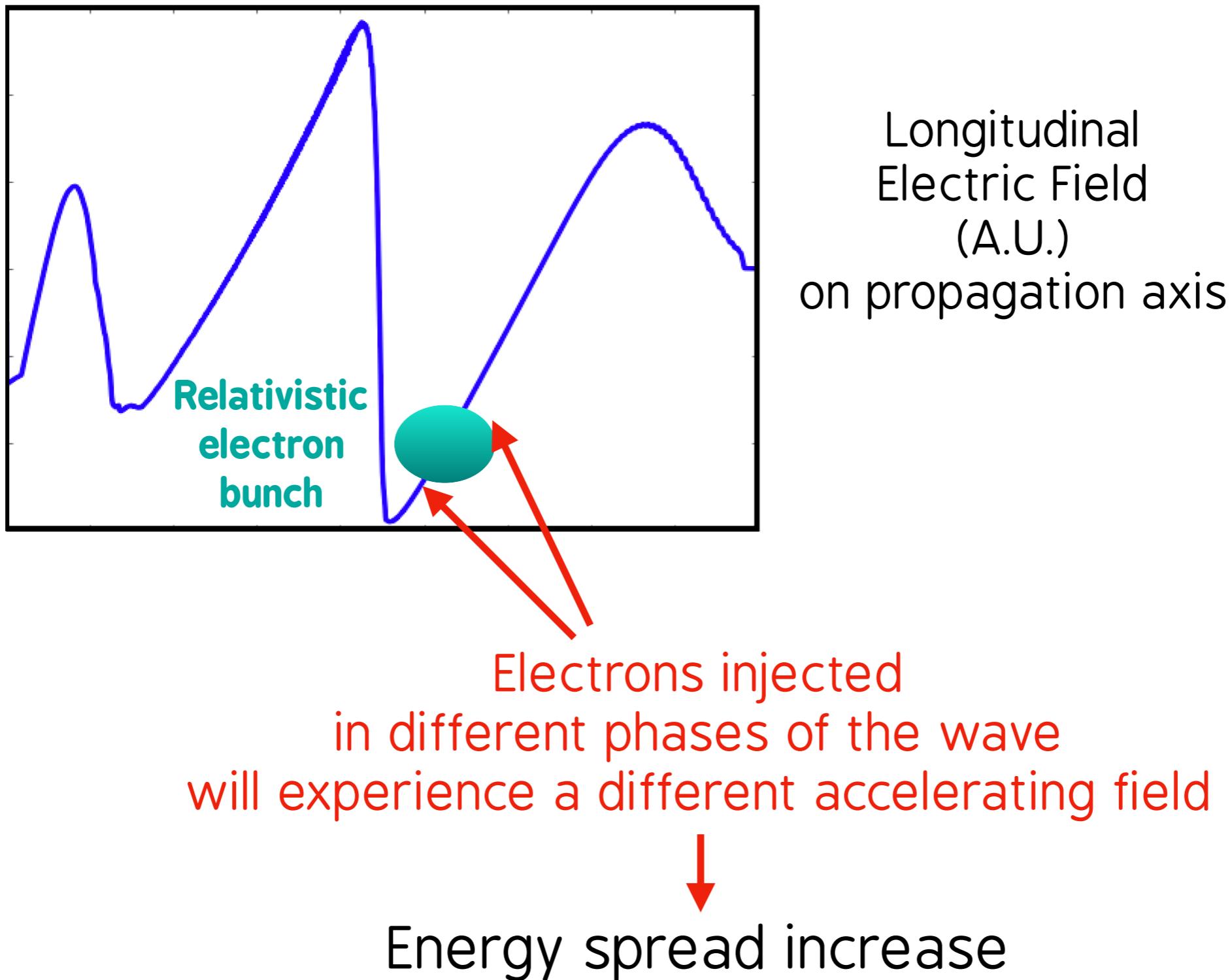
LWFA objective (not the only one): realize compact electron accelerators for applications



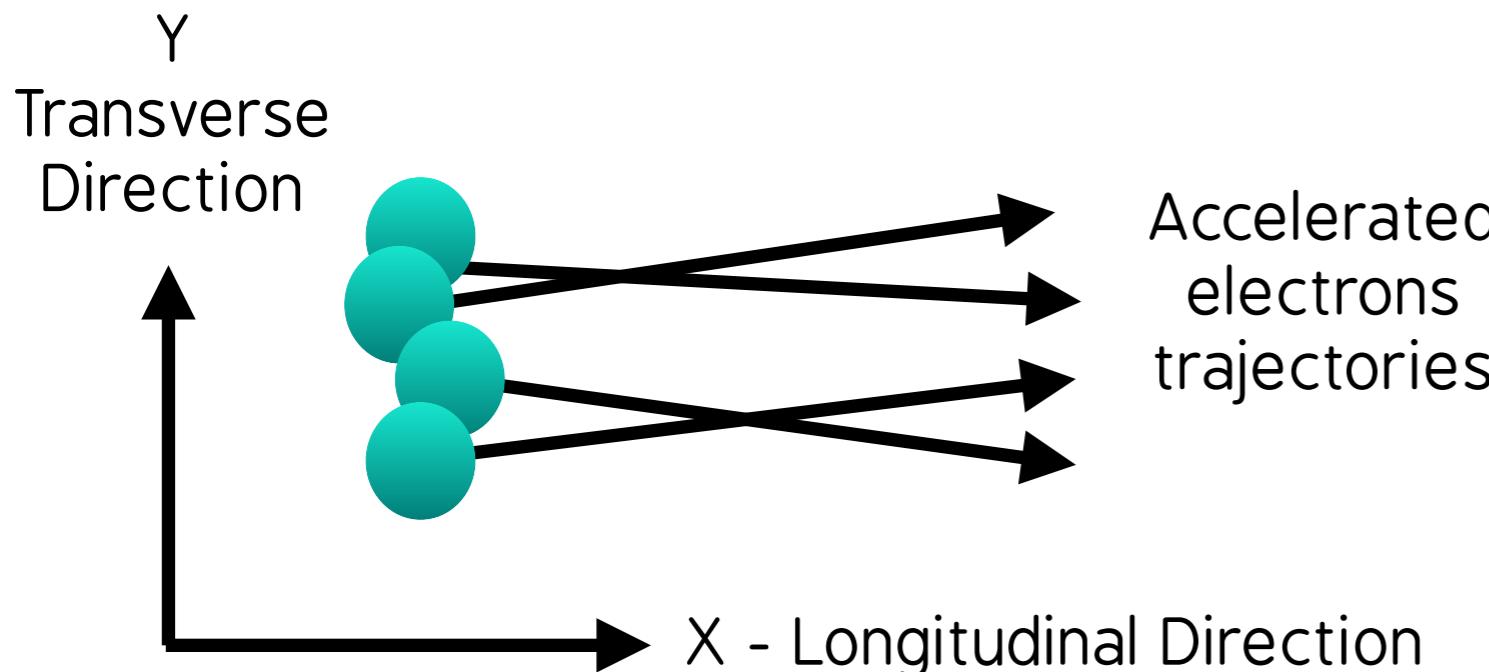
- Few electrons or many dispersed in space
- High divergence
- Different Energies (high energy spread)
- Many electrons in a small volume
- Low divergence
- Similar Energies (low energy spread)



LWFA challenges: reduce the energy spread

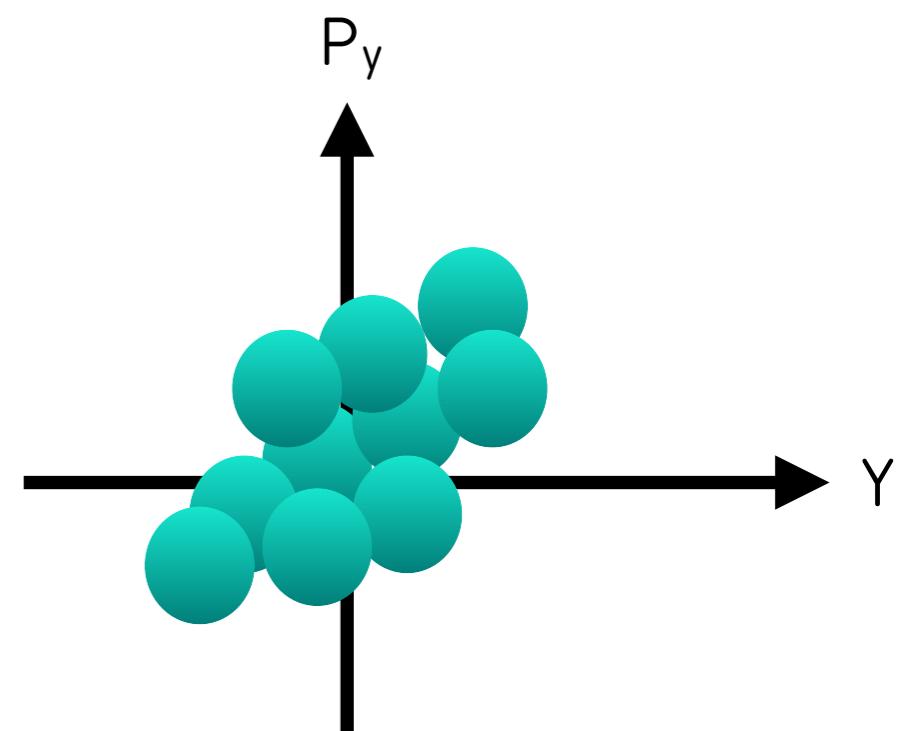


LWFA challenges: lowering the emittance



Accelerated
electrons
trajectories

Bunch distribution
in the transverse phase space



Most applications of accelerated beams require:

- Small transverse size (i.e. small σ_y)
- Small divergence (i.e. small $\sigma_{p_y}/\text{Energy}$)



**Minimize
Transverse Emittance**

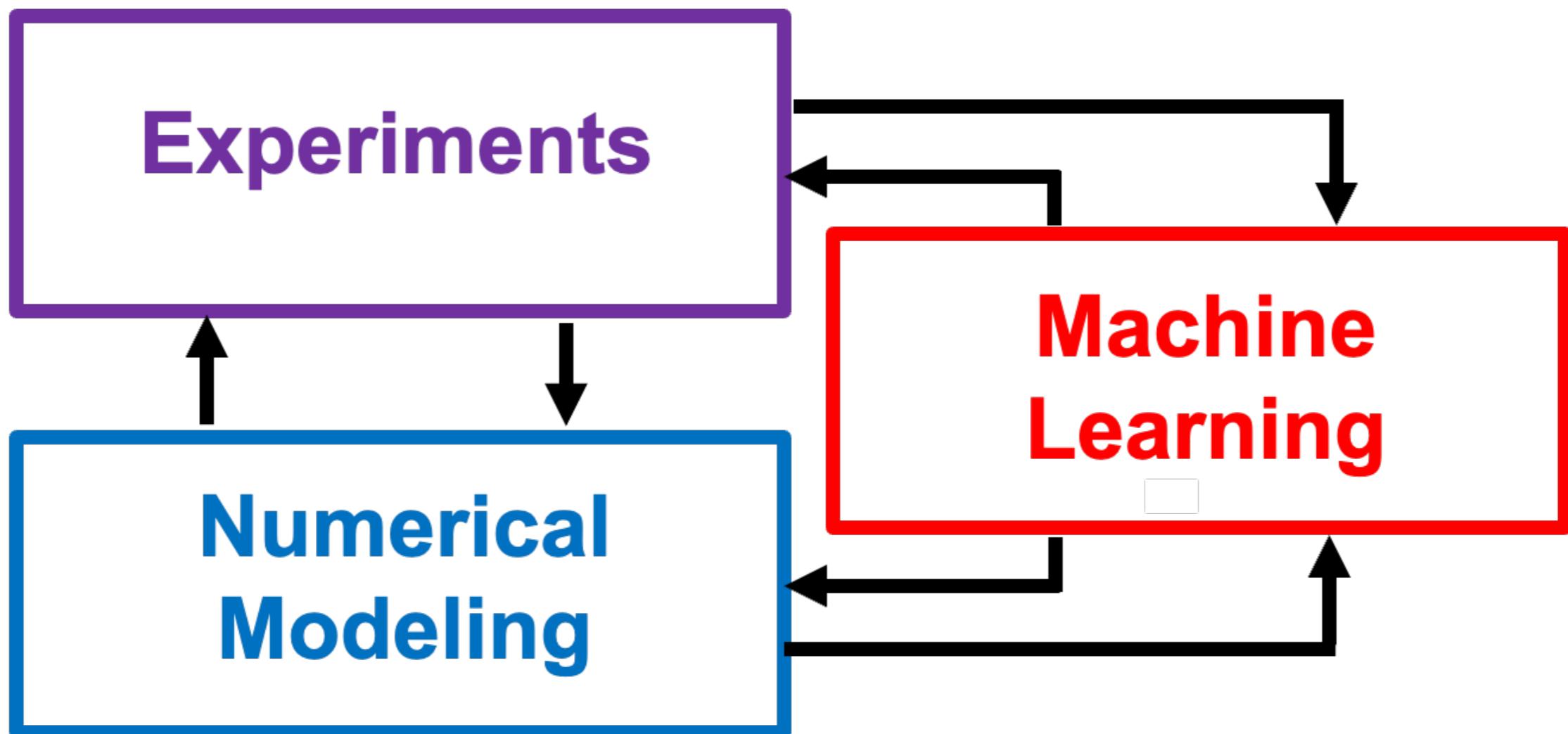
**Transverse
Normalized
Emittance**

$$\epsilon_{ny} = \frac{1}{m_e c^2} \sqrt{\sigma_y^2 \sigma_{p_y}^2 - \sigma_{y p_y}^2}$$

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LWFA investigation techniques



Why numerical simulation is necessary for LWFA?

- **No general analytical solutions are available**
- **You cannot measure everything simultaneously**
- **Before the experiment:**
 - Study new physical phenomena
 - Conceive new kind of experiments
 - Design experiments (also using Machine Learning)
- **After the experiment:**
 - Analyze the data (also using Machine Learning)
 - Understand the physics

Model for Laser-Plasma Interaction in LWFA

Complete Maxwell-Vlasov system

Plasma distribution function

$f(x, y, z, p_x, p_y, p_z, t) \longrightarrow \text{6 dimensions + time!}$

Coupled to the electromagnetic fields \longrightarrow **Non-linearity**

$$\frac{\partial f}{\partial t} + \beta c \cdot \nabla_x f - e(E + \beta c \times B) \cdot \nabla_p f = 0 \leftarrow \text{Collisions neglected}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad \begin{matrix} \text{Current density} \\ J \text{ of the plasma} \end{matrix}$$

$$\nabla \times B = -\mu_0 ec \left(\int \beta f d^3 p \right) + \frac{1}{c^2} \frac{\partial E}{\partial t}$$

Explorable Physics:

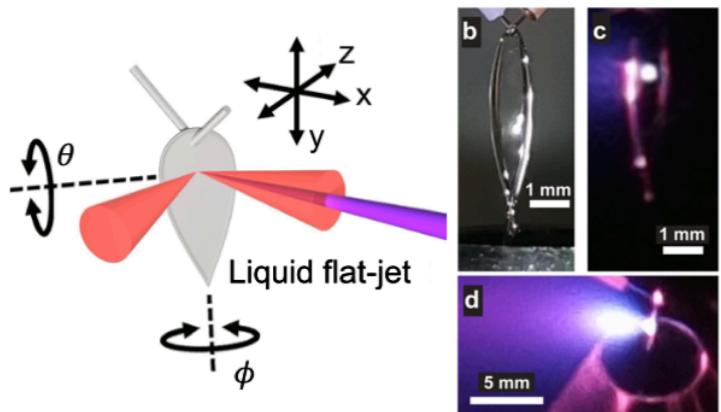
- Relativistic optics (laser self-focusing, ...)
- Nonlinear phenomena
- Wave-breaking
- Injection and acceleration of particles

Approximate solution: Particle in Cell method

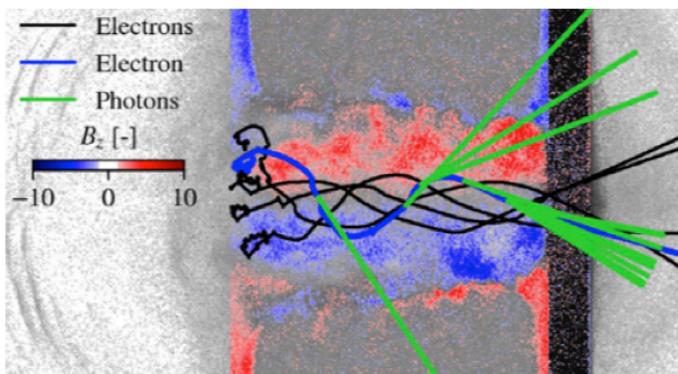
Particle in Cell (PIC) method : essential kinetic plasma investigation technique

Applications From Laboratory plasmas to Space and Astrophysical plasmas

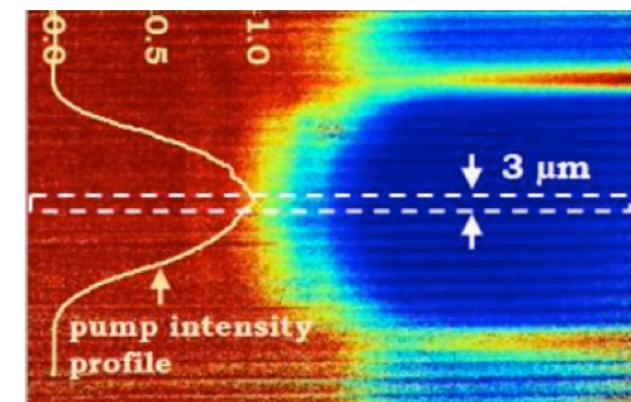
High-Harmonic Generation



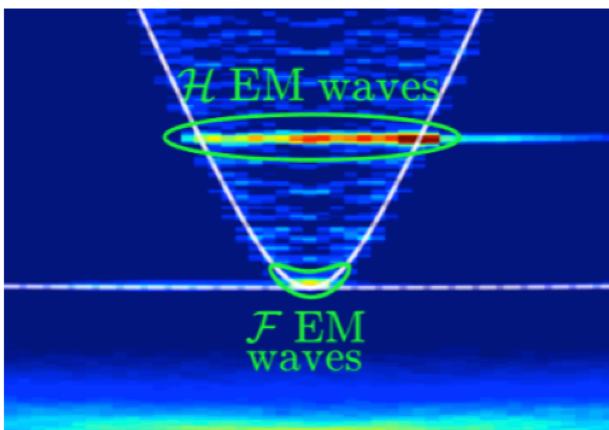
Radiation sources from DLT



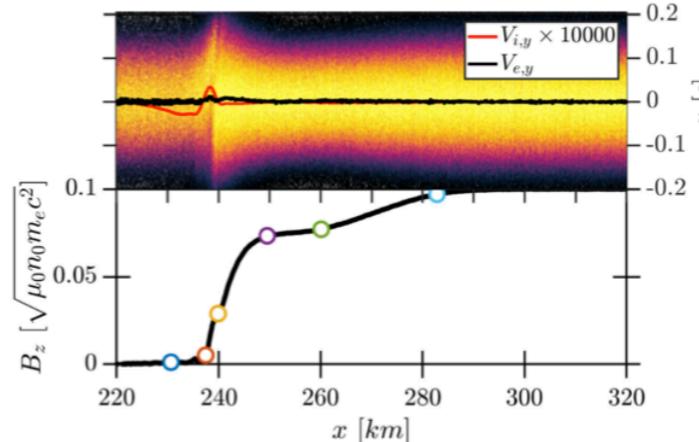
Solid to plasma transition



Solar radio-burst



Comet boundaries



Collisionless shocks & Dark Matter



- Wide range of physics applications
- Conceptually simple
- Efficiently implemented on small or massively parallel supercomputers

Some studies performed with **Smilei**)

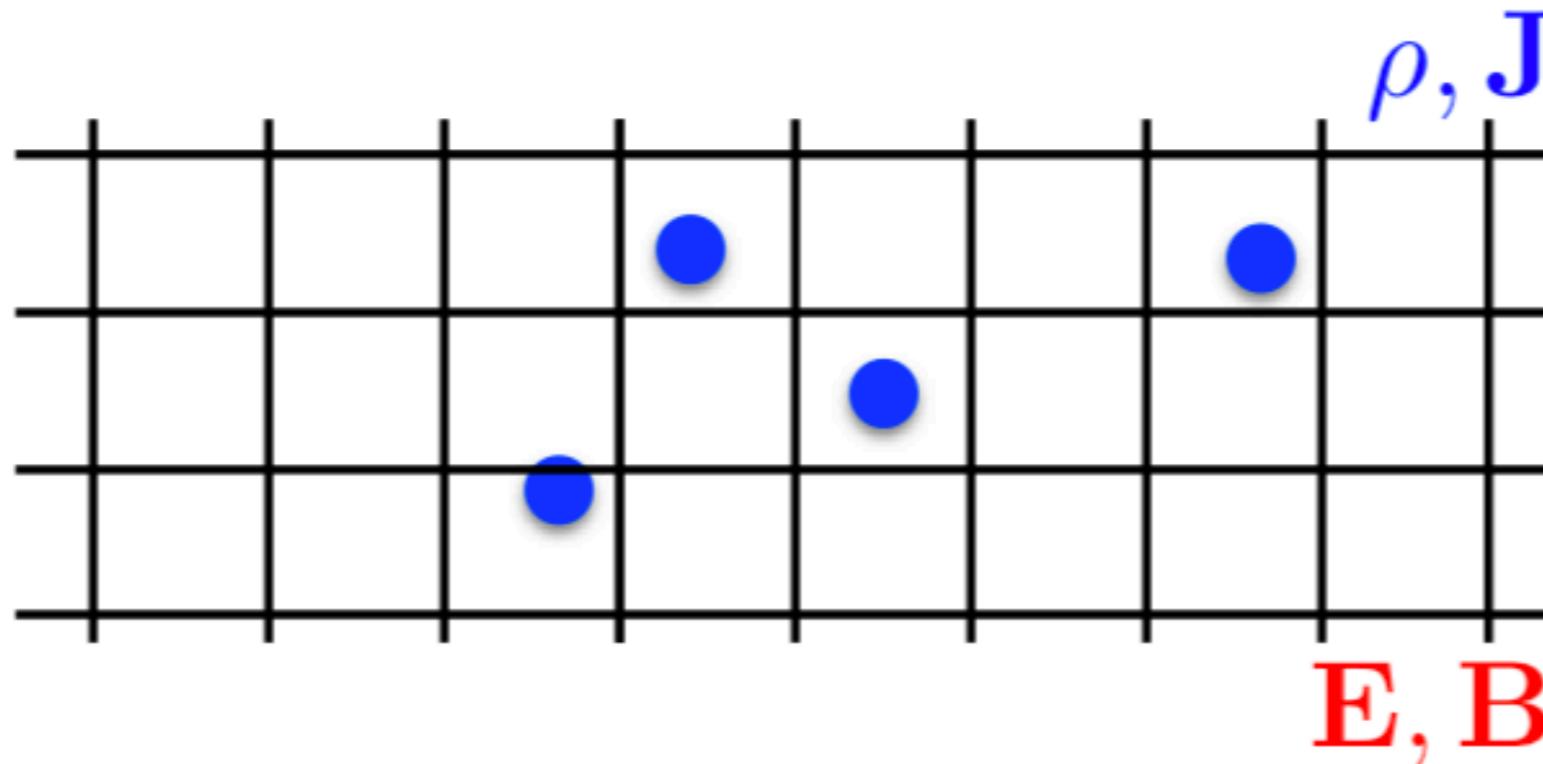
Particle in Cell concept

Sample Plasma with Macro-Particles
(1 Macroparticle = position, momentum, charge, ...)

+

Discretize space with computational grid

Define E, B, ρ, J on the grid cells



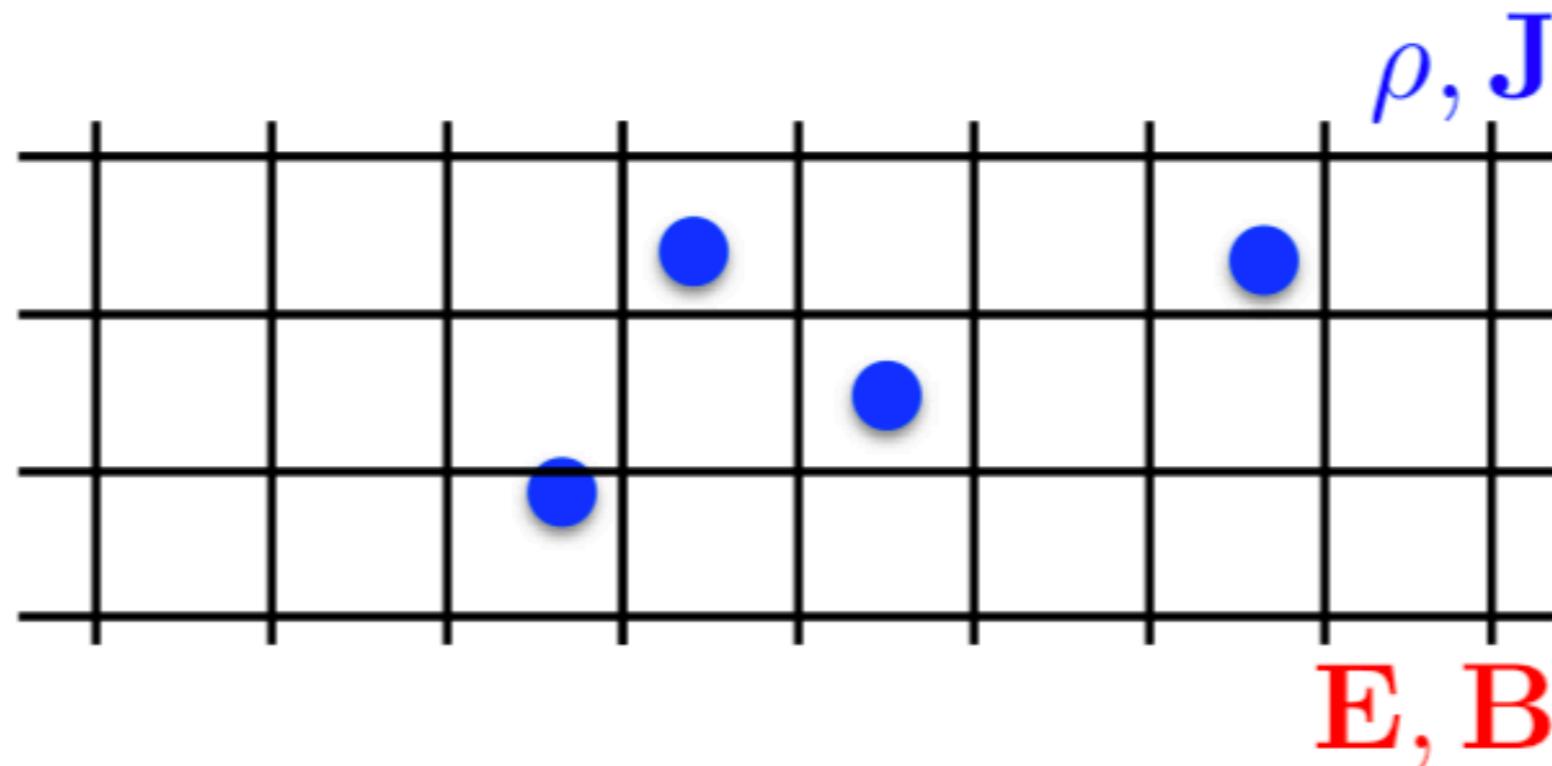
Particle in Cell concept

Macro-Particles:

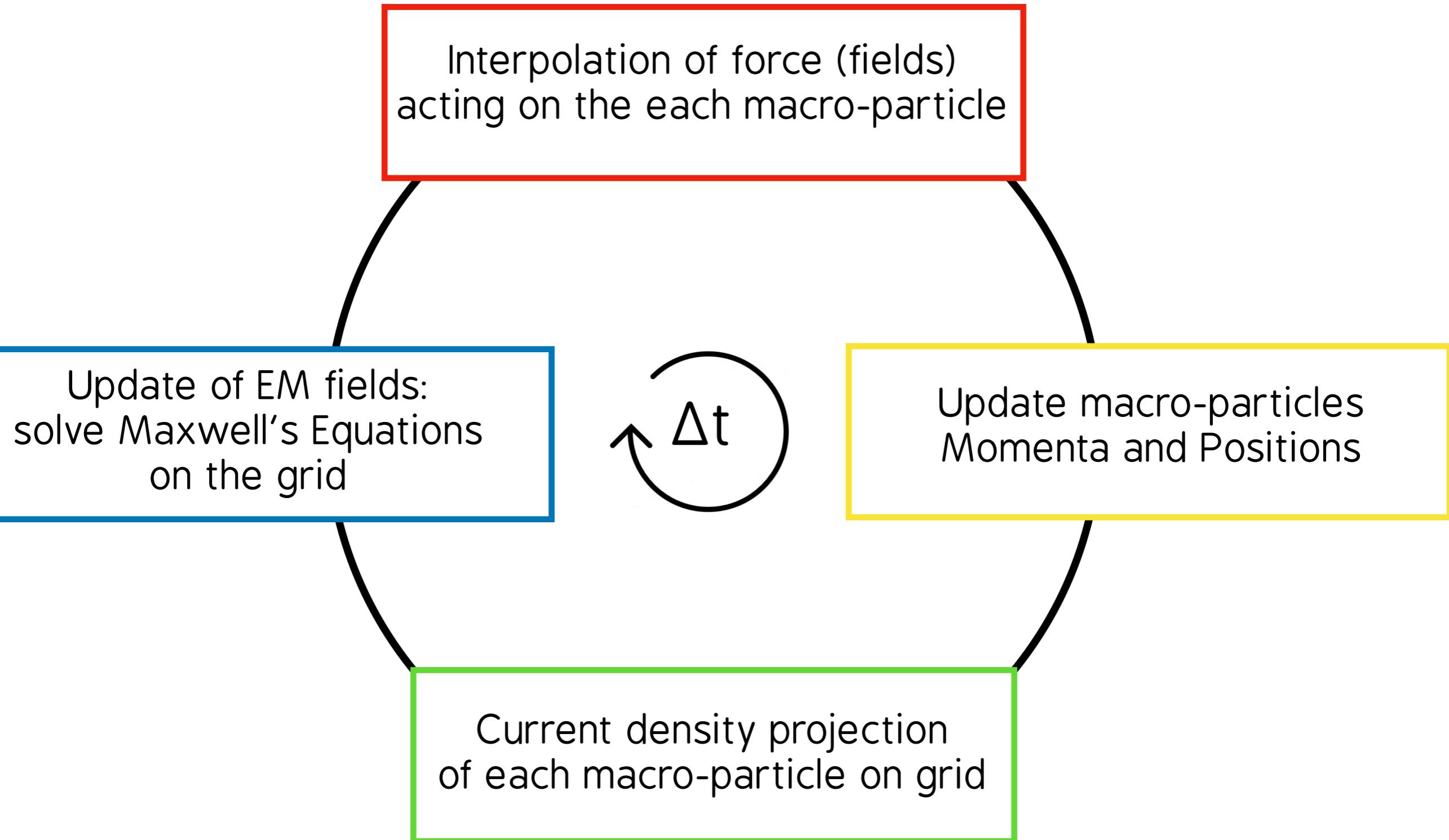
evolve following the characteristics of Vlasov Equation
(In the PIC method they look like equations of motion)

+

Electromagnetic Fields: evolve following Maxwell's Equations



Particle in Cell modelling is self-consistent



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Smilei)

User-friendly

- online: documentation, tutorials
- Python input / output
- quick visualisation library
- teaching platform
- bi-annual training workshop
- Element chat with the developers

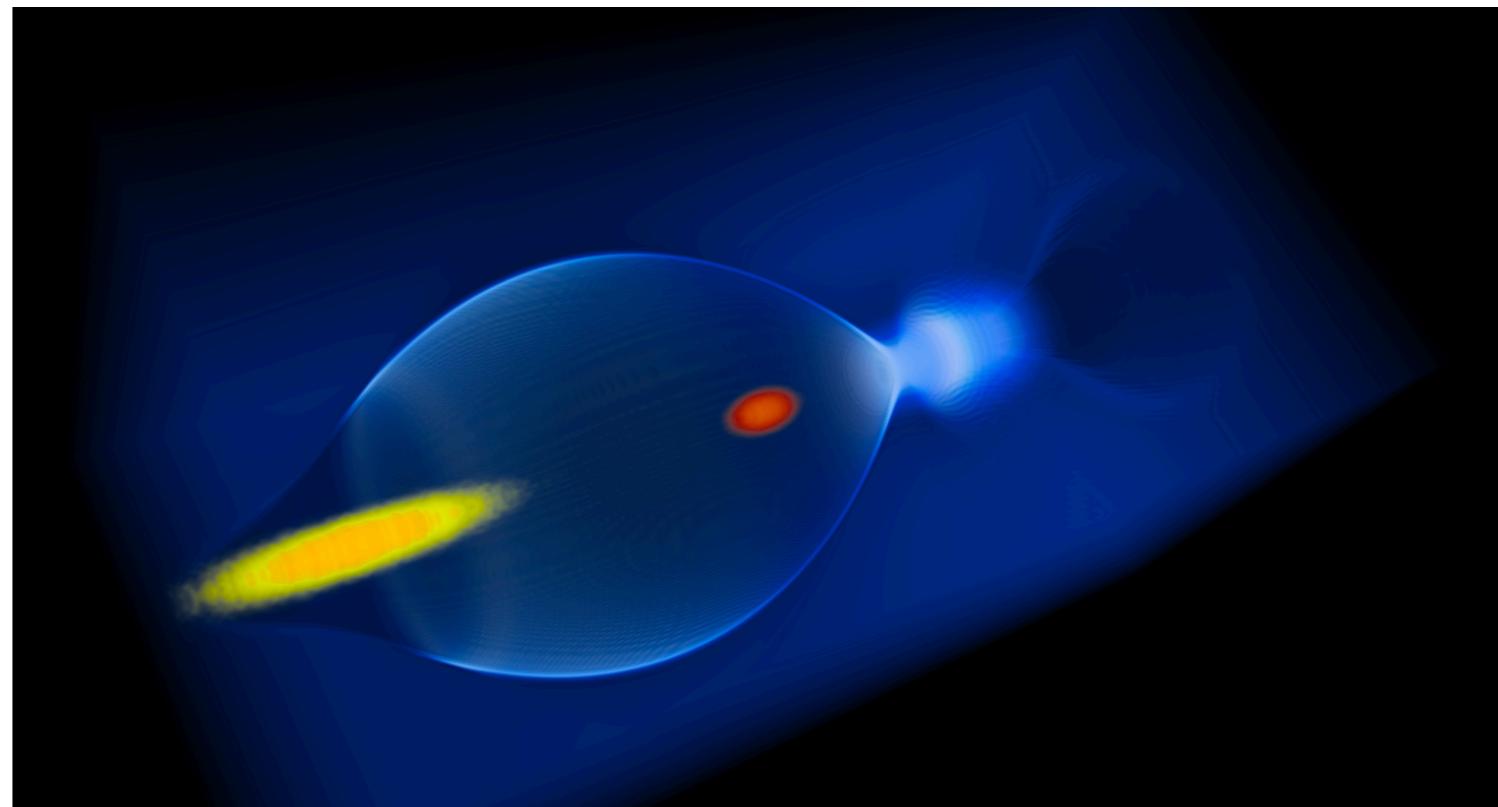
High Performance

- MPI + OpenMP parallelization
- dynamic load balancing
- adaptive vectorization
- GPU computing on both NVIDIA and AMD architectures

Multi-physics

- 1D, 2D, 3D, quasi-3D geometries
- ionization, collisions, strong-field QED
- laser envelope model
- relativistic beam field initialization

A collaborative, open source
multi-purpose Particle in Cell code
<https://smileipic.github.io/Smilei/index.html>



High quality

- developers: experts of physics and HPC
- continuously benchmarked
- GitHub bug reporting
- OpenPMD standard
- >130 publications using the code in 2023

Additional material

**Extensive Documentation
(Installation, Use, Postprocessing, ...)**

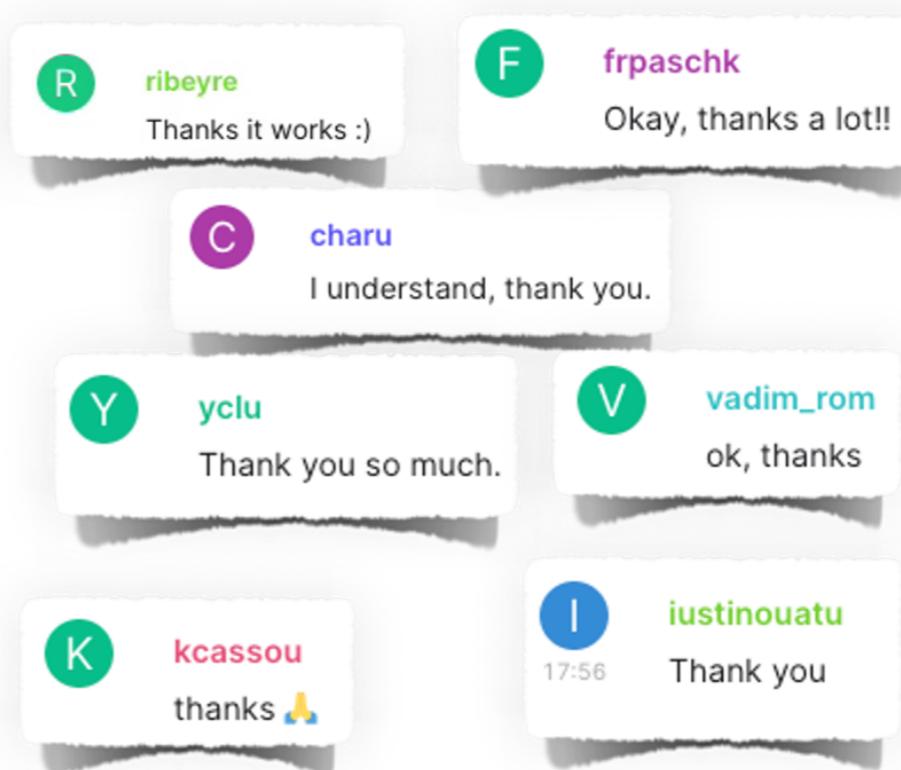
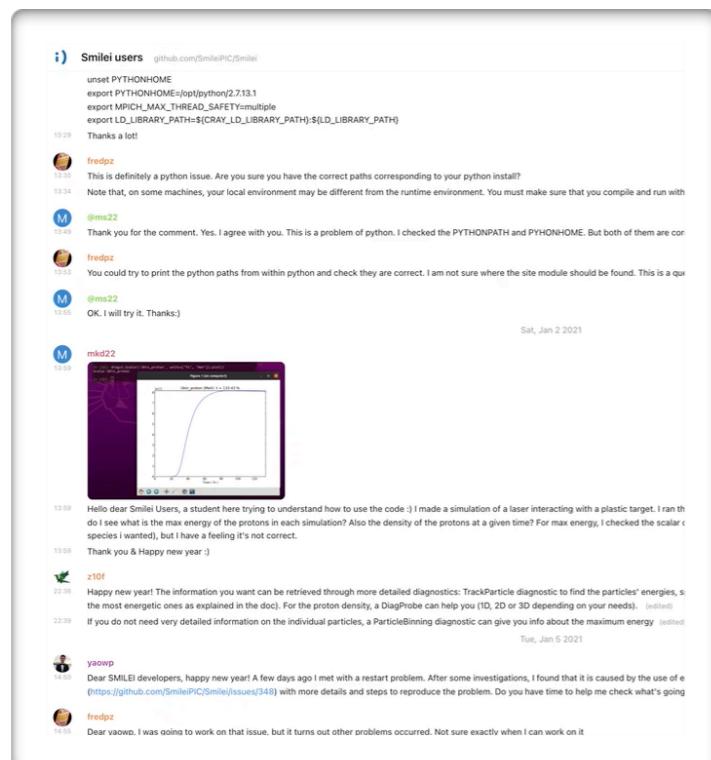


<https://smileipic.github.io/Smilei/index.html>

<https://smileipic.github.io/tutorials/>

Presentations from the 4th Training Workshop <https://indico.math.cnrs.fr/event/9577/>

Questions? We answer on the Element chat



1600 messages
in 2021

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Example of input file

```
Main(  
    geometry      = "1Dcartesian",  
    timestep      = 0.009,  
    cell_length   = [0.01],  
    ...  
)
```

```
x_center_plasma = 200.
```

```
def my_density_profile(x):  
    return exp(-(x-x_center_plasma)**2)
```

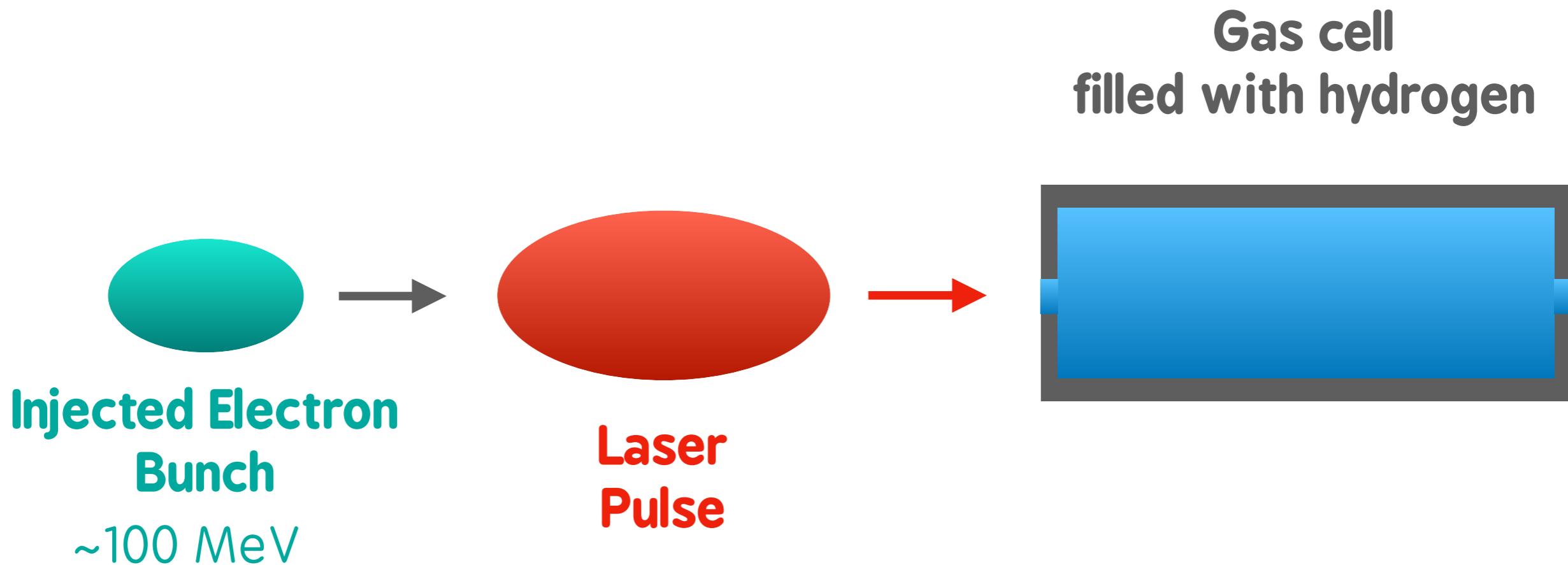
```
Species(  
    name          = "electron",  
    charge        = -1.,  
    mass          = 1.,  
    particles_per_cell = 100,  
    number_density = my_density_profile  
    ...  
)
```

- Normalised units
- Quantities can be computed at runtime

Laser /Plasma profiles = Functions
(also user-defined)

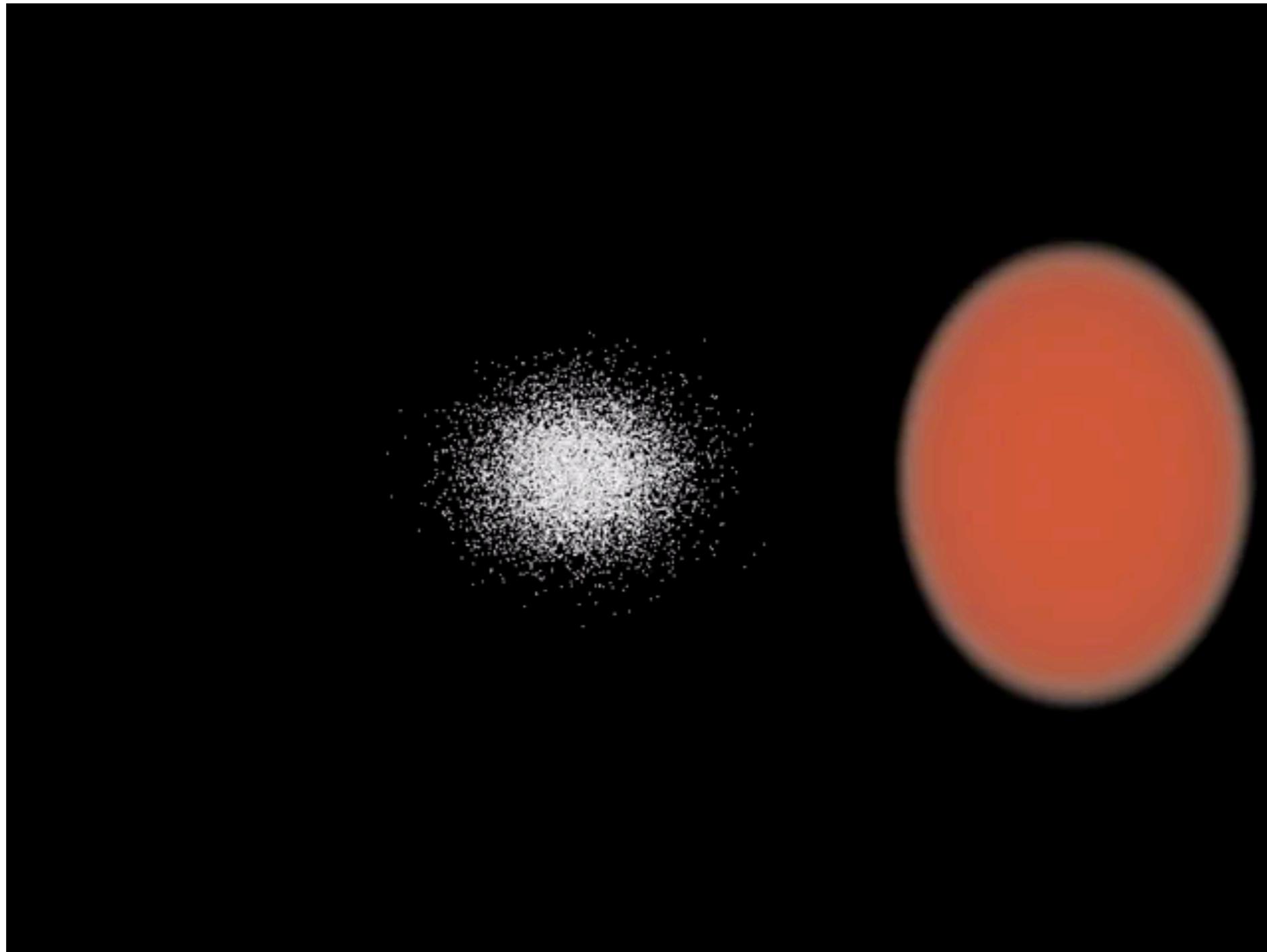
If Python can read it, SMILEI can read it

Case study: LWFA with external injection



Assumption: plasma already created in the gas cell
(the laser's repulse ionises the gas in its path)

3D rendering of LWFA with external injection



Practical material

<https://github.com/SmileiPIC/TP-M2-GI/tree/main>

Answer Form for the Exercises Link to TP documentation and Exercises

The screenshot shows a GitHub repository page for 'TP-M2-GI'. The repository has 2 branches and 0 tags. The commit history shows 80 commits by Francesco Massimo. A red arrow points from the 'Answers_Form' folder to the text 'These slides'. A green arrow points from the 'InputNamelist.py' file to the text 'Input Namelist file to run simulations'. A blue arrow points from the 'Presentation_TP.pdf' file to the text 'Postprocessing Scripts'. A purple arrow points from the 'submission_script.sh' file up to the text 'Simulation submission file'. The repository page includes links for 'Edit Pins', 'Unwatch', 'Fork', 'Star', 'About', and a link to 'smileipic.github.io/TP-M2-GI/' which is highlighted with a red box.

TP-M2-GI Public

main 2 branches 0 tags

Francesco Massimo and Francesco Massimo change environment

.github/workflows Update sphinx.yml 15 hours ago 80 commits

Answers_Form update TP 10 months ago

Postprocessing_Scripts update namelist 5 days ago

doc correction 16 hours ago

InputNamelist.py update namelist 5 days ago

LICENSE Create LICENSE 16 hours ago

Presentation_TP.pdf update presentation 2 years ago

README.md Update README.md last year

submission_script.sh change environment 10 months ago

15 hours ago

These slides

Input Namelist file to run simulations

Postprocessing Scripts

Simulation submission file

About

Numerical practical for the students of the M2 - Grands Instruments.

smileipic.github.io/TP-M2-GI/

Readme

GPL-3.0 license

Activity

2 stars

7 watching

2 forks

Report repository

Releases

No releases published

Create a new release

Practical exercises

- Read **in detail** the **TP documentation**
<https://smileipic.github.io/TP-M2-GI/index.html>
- Solve the exercises in the **TP documentation** progressively, e.g.

Exercise 1:

Assuming $\lambda_0 = 0.8\mu m$ (a Ti:Sa laser system), what is the value of the critical density n_c ?

What is the value of the reference electric field $E_0 = (2\pi m_e c^2)/(e\lambda_0)$?

This choice of λ_0 will be used throughout all subsequent exercises.

Hint: Some lines at the start of the `InputNamelist.py` file can help you in the calculations.

Exercise 5:

In the next exercise we will check that the Gaussian laser pulse diffracts following the theory for a Gaussian beam [Siegman]: $w(x) = w_0 \sqrt{1 + x^2/x_R^2}$, where w_0 is the laser waist size at the focal plane position, $w(x)$ the laser waist size at propagation distance x , x_R is the Rayleigh length $x_R = \pi w_0^2/\lambda_0$.

What is the theoretical Rayleigh length x_R ?

Exercise 10:

Launch a new simulation with $a_0=1.8$. This simulation will be in the nonlinear regime ($a_0 > 1$), so the plasma wave will not be sinusoidal. You can visualize both the normalized absolute value of the envelope of the laser field and the electron number density by defining a transparency for the parts where the latter field is lower than a threshold v_{min} :

```
Env_E = S.Probe.Probe1("Env_E_abs",units=["um"],cmap="hot",vmin=0.8,transparent="unde  
Rho = S.Probe.Probe1("-Rho/e",units=["fs","um","1/cm^3"],cmap="Blues_r",vmin=0.,vma  
happi.multiSlide(Rho,Env_E,xmin=0,figure=10, xlabel="x [um]",ylabel="y [um]")
```

Using `timestep=2500` in the definition of `Env_E` and `Rho`, and then using `multiPlot` instead of `multiSlide`, you should have a plot of the data at half of the propagation length.

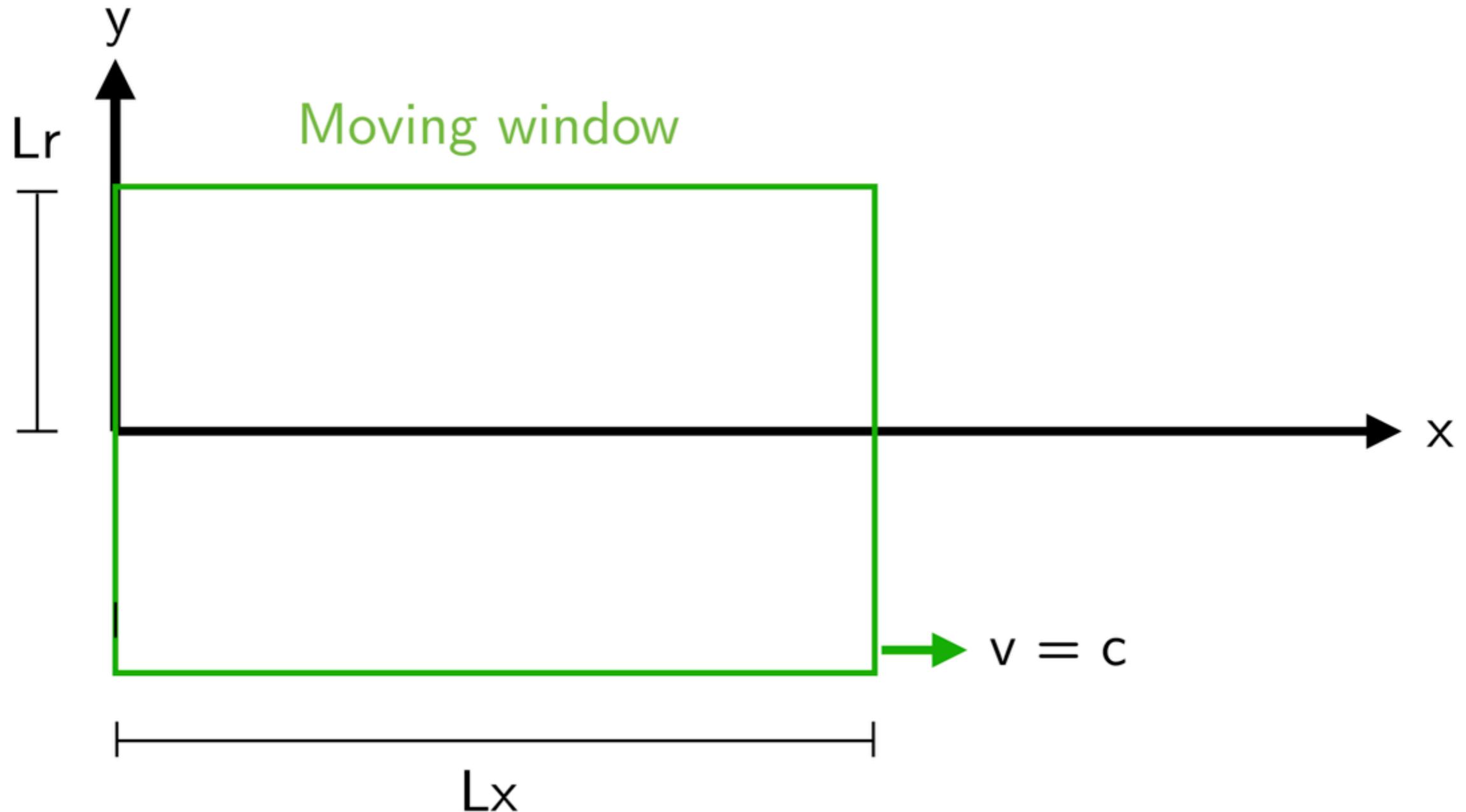
Include this image in your answers.

- Run simulations when necessary, following the instructions in the **TP documentation**
- Fill the answers report **Answers_Form.docx**
(You can download it from GitHub
<https://github.com/SmileiPIC/TP-M2-GI/tree/main>)

Suggestions

- Again read **in detail** the **TP documentation**
- **Understand** the physical set-up
- **Any doubts? Ask the instructor**
- Solve the exercises **progressively**
- Create one folder for each simulation asked by the exercises
(to **avoid losing data**)
- Feel free to adapt the commands in the **TP documentation**
- When an image is asked for the report, save it or make a screenshot
- **Better do few exercises but understand them at 100%**

Part 1: Exploring the Input Namelist (Exercises 1-2)



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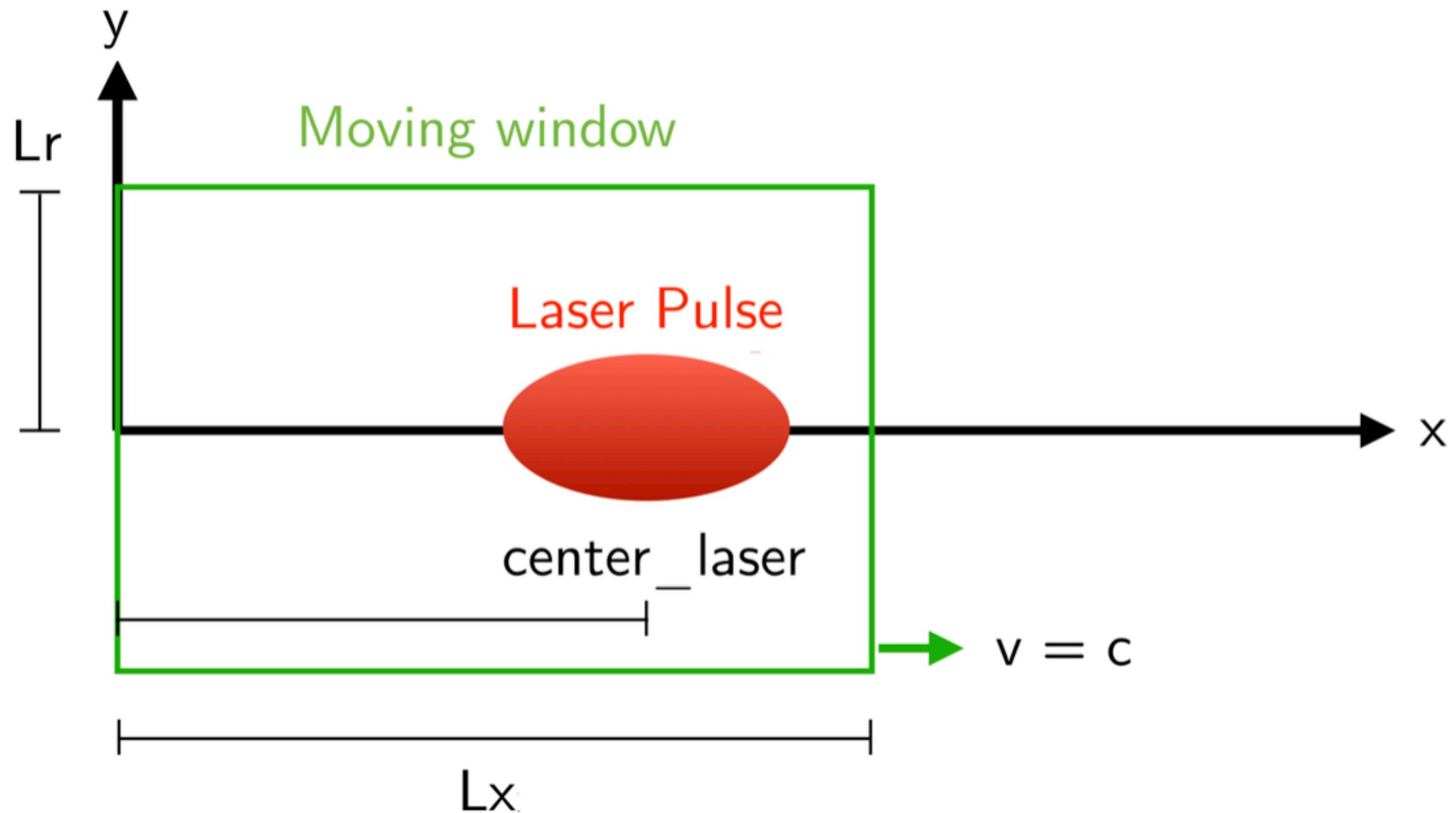
Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

Part 2: Laser pulse in vacuum (Exercises 4-6)



Part 2: Laser pulse in vacuum (Exercises 4-6)

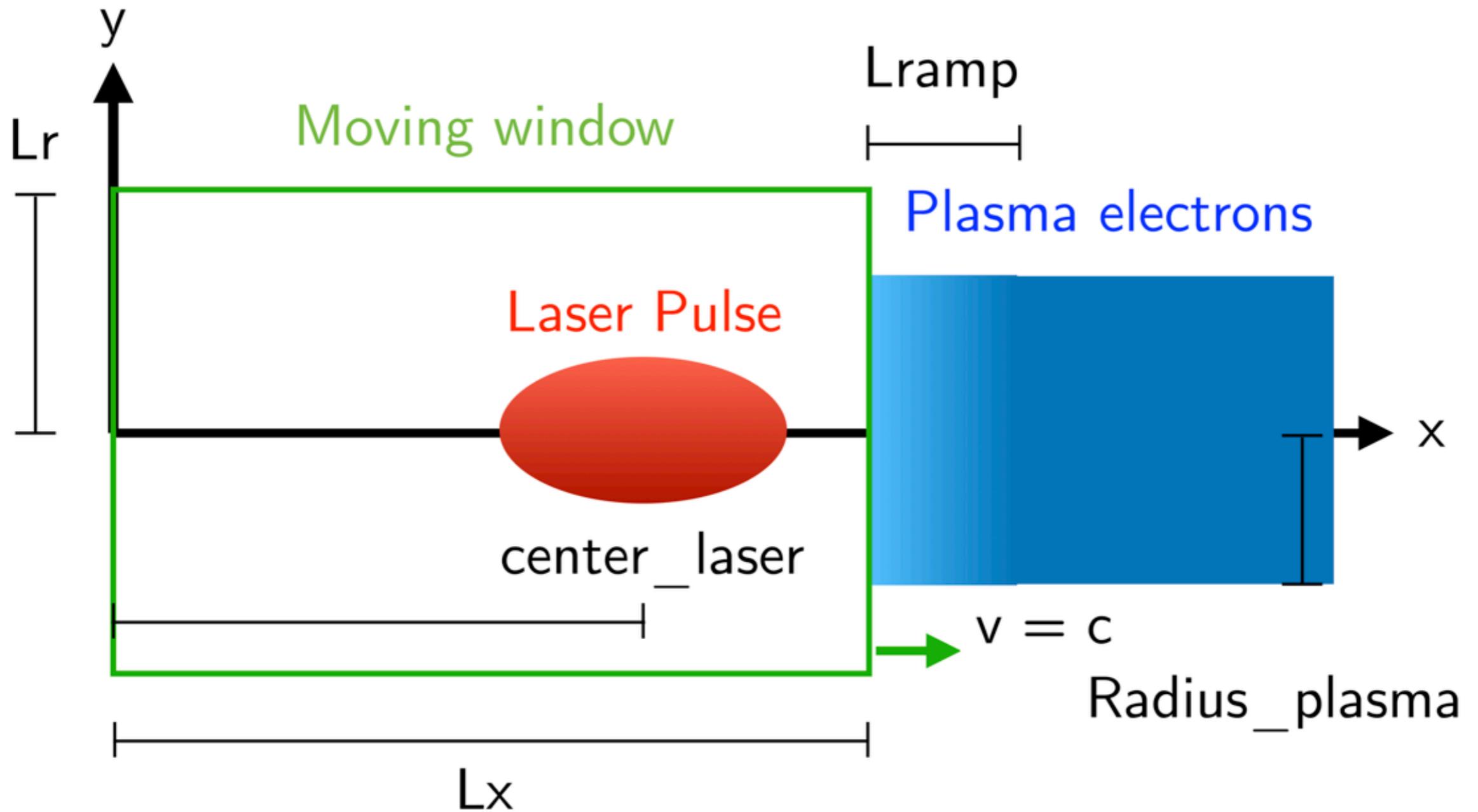
Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

Part 3: Laser Wakefield Excitation (Exercises 7-11)



Part 3: Laser Wakefield Excitation (Exercises 7-11)

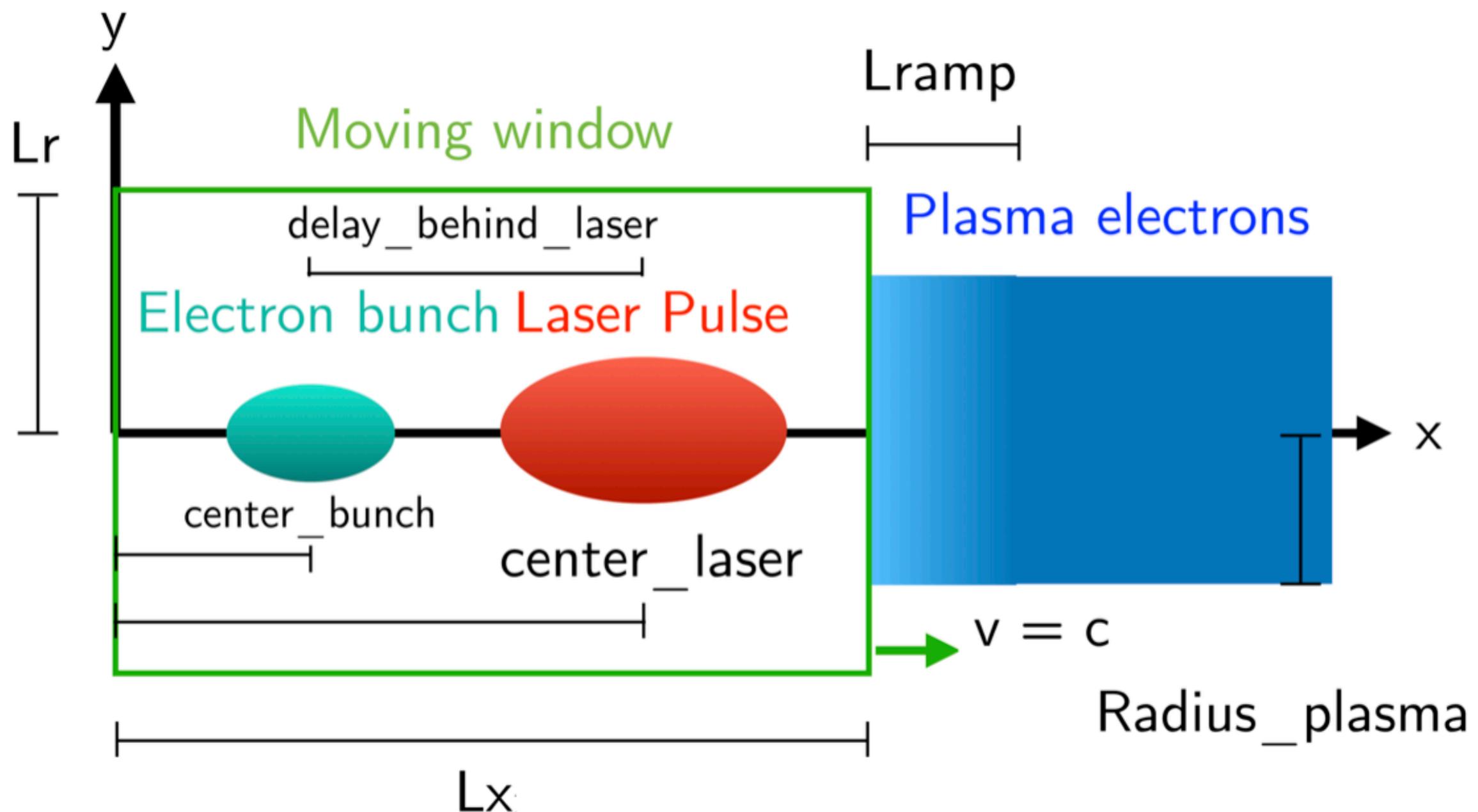
Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

Part 4: Laser Wakefield Acceleration of an electron bunch (Exercises 12-20)



Input Namelist structure

- Main Block
- Moving Window Block
- Laser Envelope Block
- Species Block (for the plasma)
- Species Block (for the relativistic electron bunch)
- Diagnostic Blocks (for Postprocessing)

Blue: Active

Gray: Commented = Inactive

Postprocessing for the practical

Included in the code: the Python postprocessing library **happi**

```
$ ipython  
In [1]: import happi
```

Diagnostics available for this practical:

- 1D Probe on the x axis (electromagnetic fields, density)
- 2D Probe on the xy plane (electromagnetic fields, density)
- DiagTrackParticles for the bunch electrons (phase space data)

Tips:

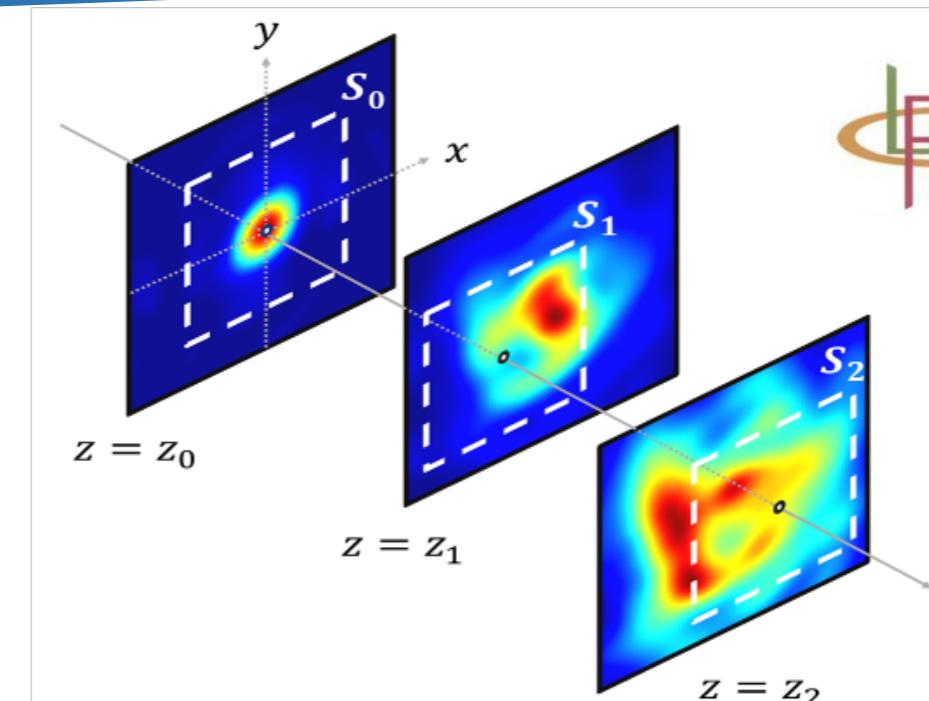
- Open the **Ipython** interface (command **ipython** in the terminal)
- Copy and paste the happi commands from the handouts
- Adapt them for your purposes
- Use the post processing scripts available (see handouts)

Questions?

Additional Slides

Some current LWFA research themes (1)

Realistic laser pulses in PIC simulations yield
Accurate reconstructions of experimental data



I. Moulanier et al.,
Physics of Plasmas (2023)

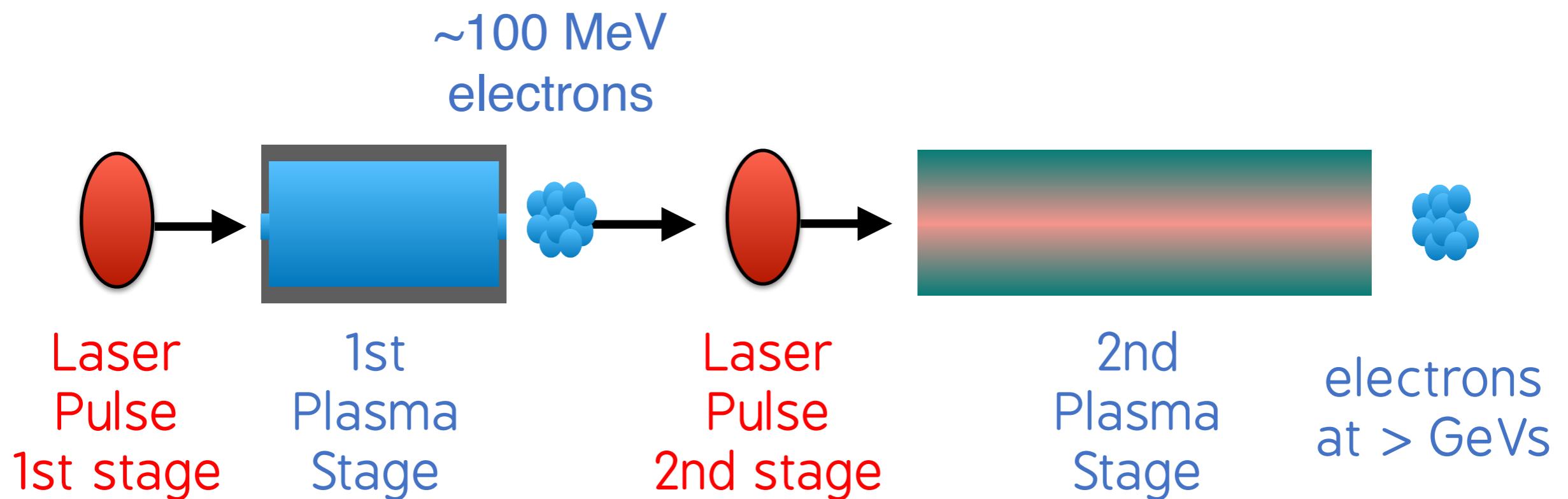
I. Moulanier et al.,
J. Opt. Soc. Am. B **40**(9), 2450-2461 (2023)

Internship at LPGP: Advanced electric field reconstruction analysis

Use advanced phase reconstruction algorithm to reconstruct laser field

Some current LWFA research themes (2)

Making LWFA scalable: Multi-stage experiments

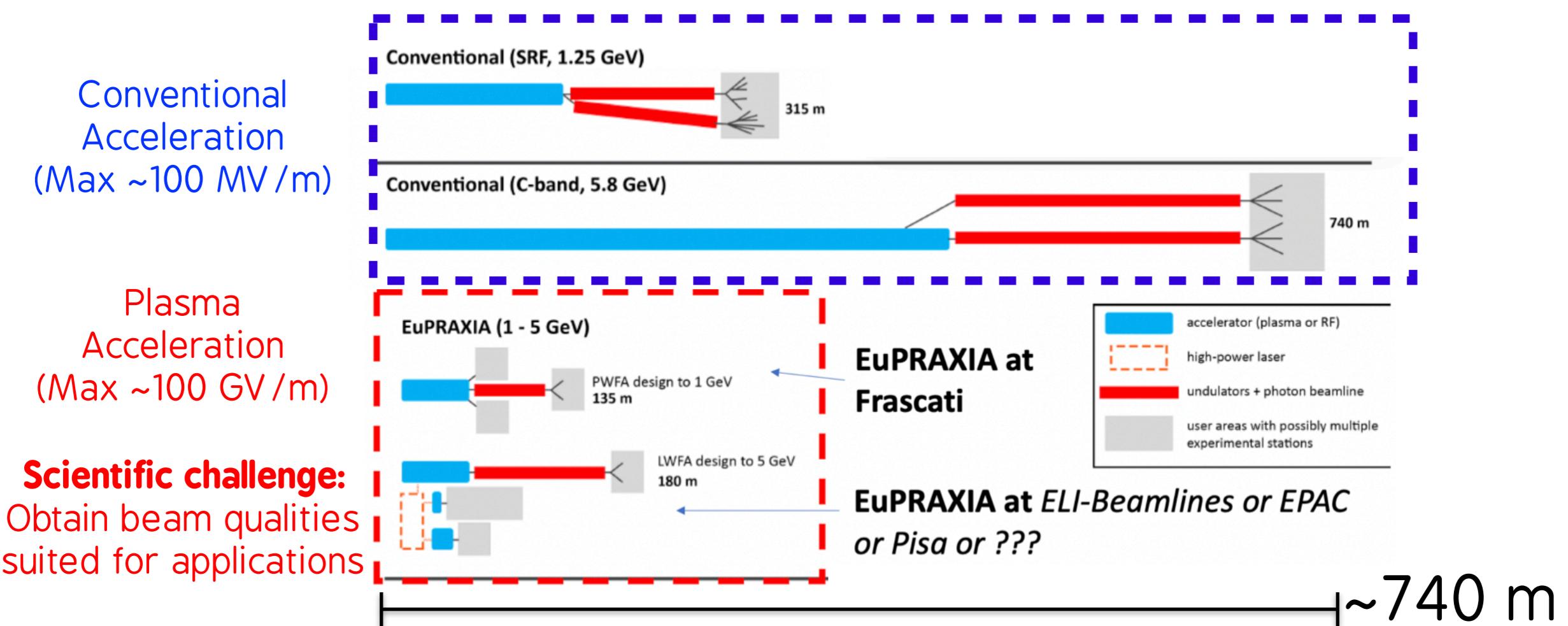


Some current LWFA research themes (3)



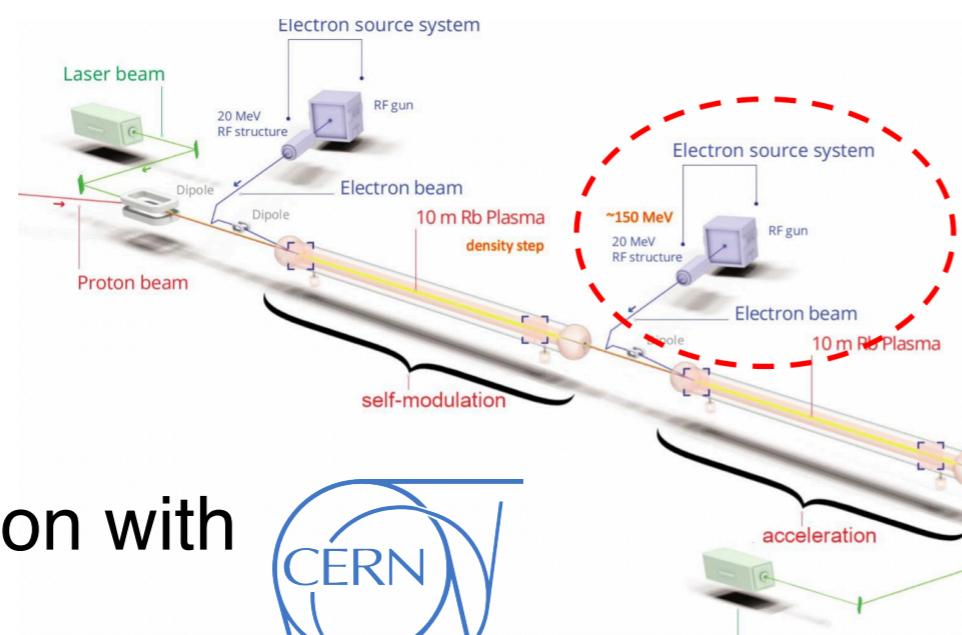
Objective: build a European, large scale, distributed plasma acceleration facility for users

R. Assmann, EuPRAXIA Preparatory Phase kick-off meeting (Nov 2022)



Some current LWFA research themes (4)

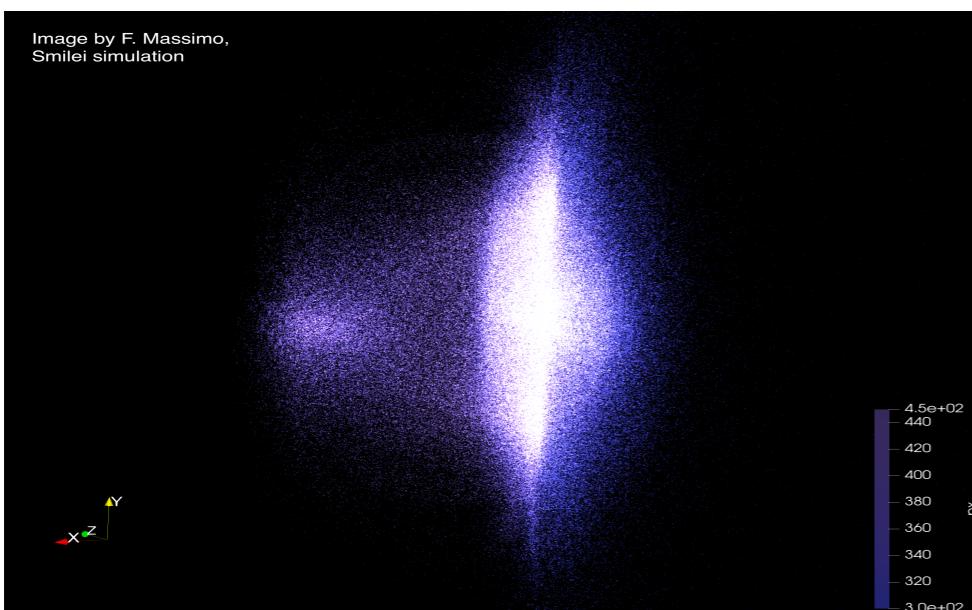
Electron Accelerator driven by a Reliable Laser for Industrial uses (EARLI)



Can we use
a laser Wakefield accelerator
as electron injector in project



Collaboration with

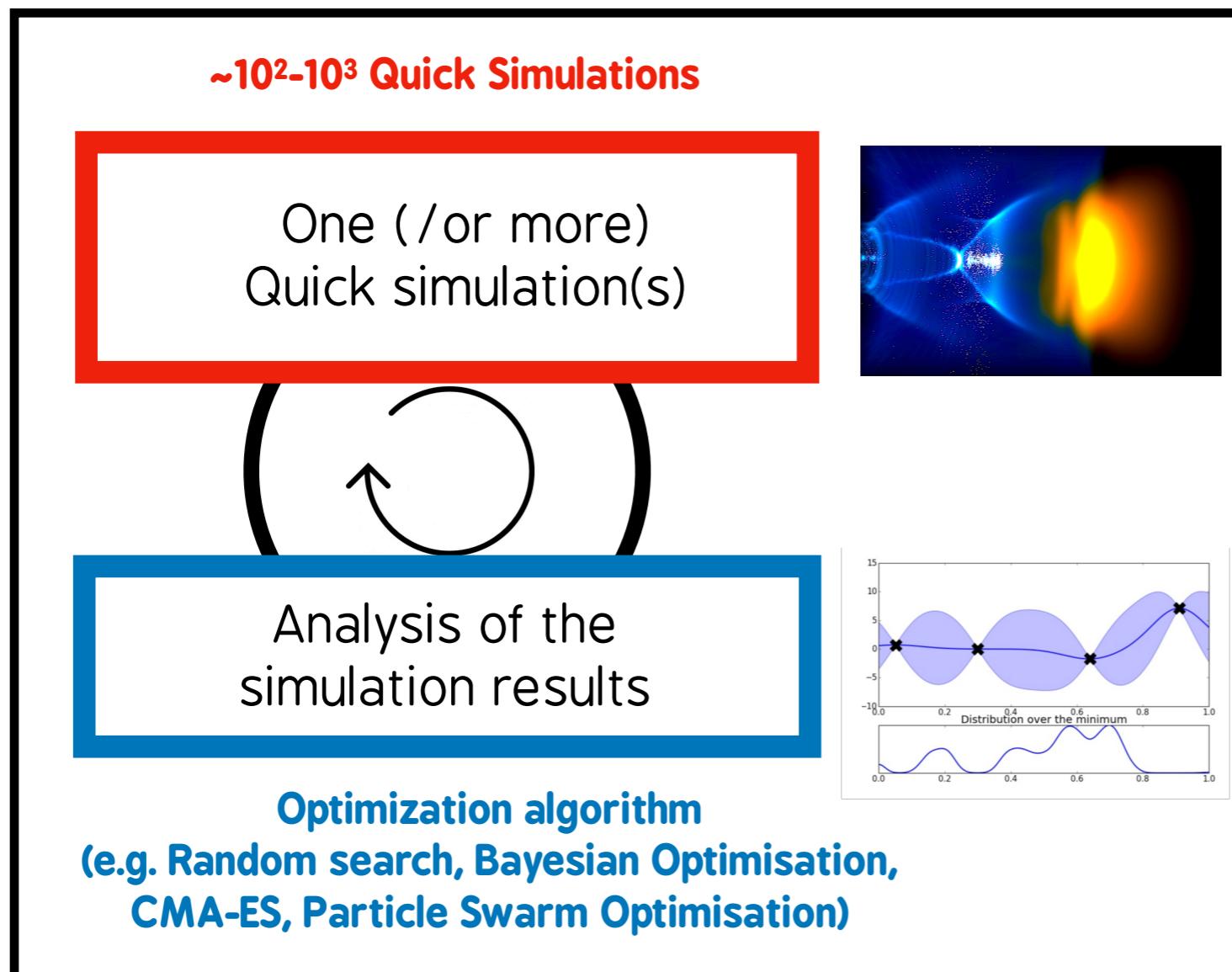


Objective: build a LWFA
to inject an electron beam
in proton-driven waves
propagating in a 10 m plasma

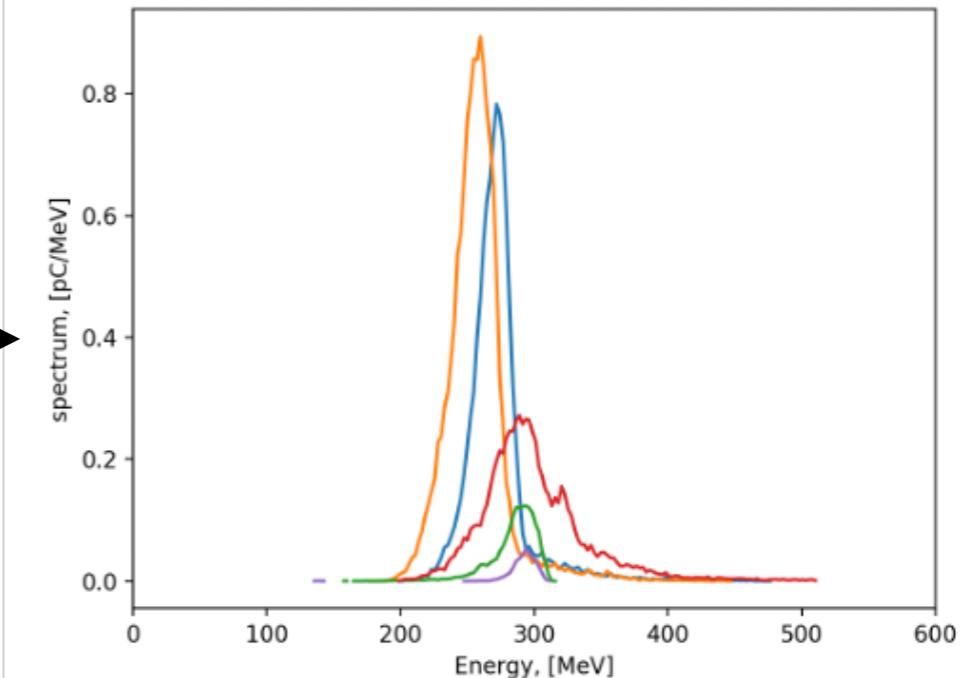
Electron beam at plasma exit, Smilei simulation

Some current LWFA research themes (5)

Machine Learning and AI for LWFA



Optimized Electron Spectra



P. Drobniak and IJClab,
2021