POLITECNICO
MILANO 1863

Smilei)

Teaching computational plasma physics at Politecnico di Milano

Arianna Formenti

March 9th, 2022 | Ecole Polytechnique

3rd Smilei user & training workshop

Politecnico di Milano

largest technical university in Italy

- ~ 50k students (~1.5k PhD), ~3.5k academic staff
- MSc in Nuclear Engineering: 80 students (AY 2021/22)
- PhD in Energy and Nuclear Science and Technology with several PhDs in laser-plasma & nuclear fusion

Our team

- lead by prof. Matteo Passoni
- @ Micro and Nanostructured Materials Lab, Department of Energy
- 6 PhDs, 2 post-docs, 4 academic staff
- **projects**
    - ERC CoG 2015-2020 ENSURE
    - ERC PoC INTER 2017-2018
    - ERC PoC PANTANI recently accepted
    - several EUROfusion projects both in ICF & MCF
- **cross-disciplinary**: materials science, nuclear engineering, plasma physics, computational physics
- **didactic activities** in plasma, nucler, atomic & solid state physics

picture crafted with care by artist Elena Tonello

NanoLab

www.ensure.polimi.it

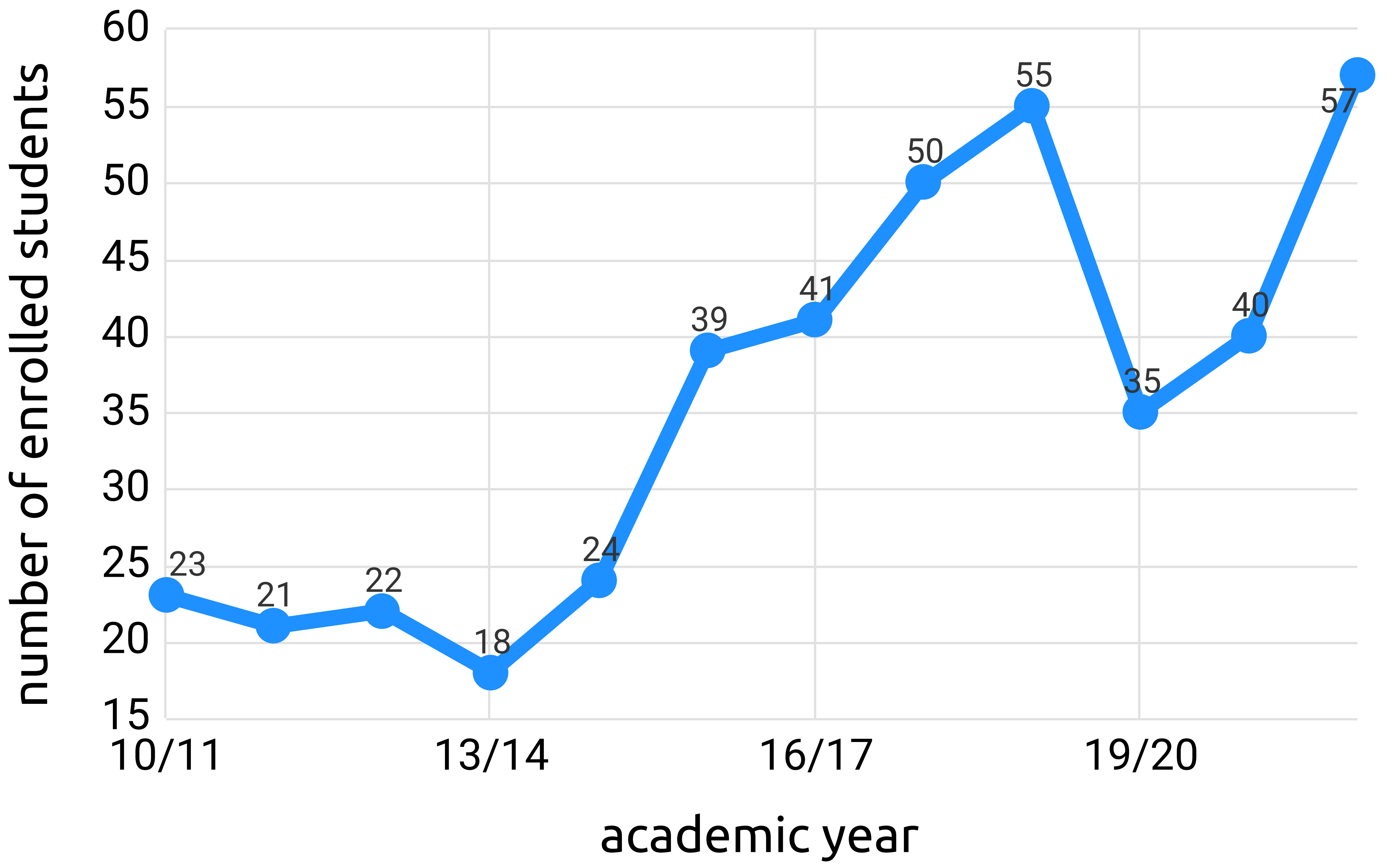
Plasma physics course

main course addressing plasma-related topics

main covered topics

- fundamental plasma parameters
- guiding center theory
- methods for the description of a plasma
- waves in a plasmas
- emission of radiation in a plasma
- laser-plasma interaction
- magnetically-confined plasmas
- collisions in a plasma
- controlled thermonuclear fusion

~ 100 hours in class for 10 ECTS



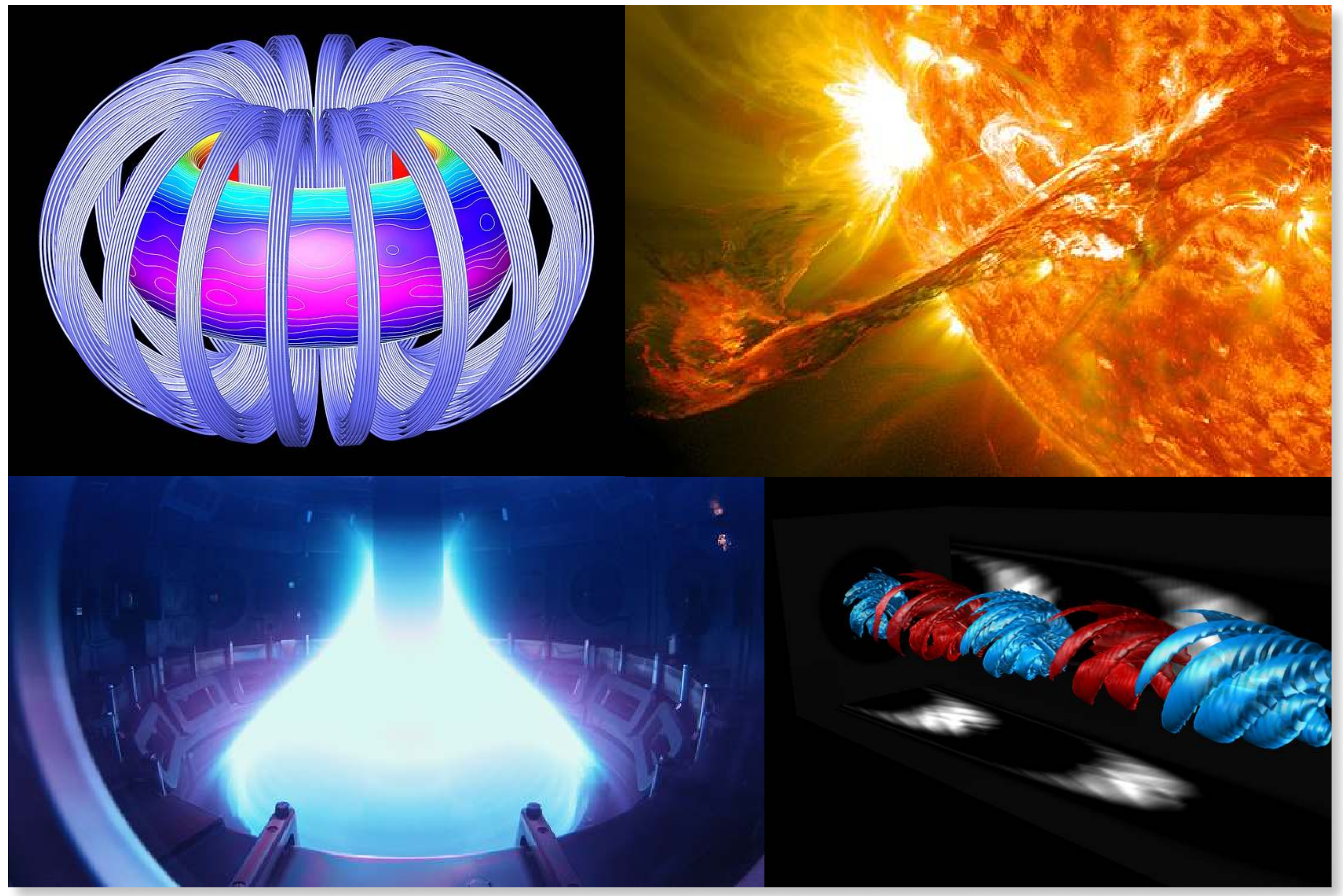
students

MSc in nuclear, physics, mathematical & materials engineering coming from a broad range of BSc

What about computational plasmas?

several courses on various “computational physics” topics but very few plasma-related ones

ADVANCED PROGRAMMING FOR SCIENTIFIC COMPUTING
COMPUTATIONAL FLUID DYNAMICS OF REACTIVE FLOWS
COMPUTATIONAL MECHANICS
COMPUTATIONAL TECHNIQUES FOR THERMOCHEMICAL PROPULSION
COMPUTATIONAL BIOMECHANICS LABORATORY
BIOINFORMATICS AND COMPUTATIONAL BIOLOGY
COMPUTATIONAL MODELING IN ELECTRONICS AND BIOMATHEMATICS
COMPUTATIONAL BIOLOGY OF THE HEART
LOW FREQUENCY COMPUTATIONAL ELECTROMAGNETICS
COMPUTATIONAL FLUID DYNAMICS
COMPUTATIONAL METHODS FOR RELIABILITY, AVAILABILITY AND MAINTENANCE
COMPUTATIONAL MECHANICS AND INELASTIC STRUCTURAL ANALYSIS
COMPUTATIONAL STATISTICS
COMPUTATIONAL FINANCE
ADVANCED COMPUTATIONAL MECHANICS
ELEMENTS OF COMPUTATIONAL STRUCTURAL ANALYSIS
COMPUTATIONAL STRUCTURAL ANALYSIS
COMPUTATIONAL MODELING FOR MATERIALS ENGINEERING
COMPUTATIONAL DESIGN IN ARCHITECTURE
IMAGE ANALYSIS AND COMPUTER VISION
METHODS FOR BIOMEDICAL IMAGING AND COMPUTER AIDED SURGERY
COMPUTER ANIMATION
ARTIFICIAL INTELLIGENCE AND ADVANCED SIMULATION FOR THE SAFETY, RELIABILITY AND MAINTENANCE OF ENERGY SYSTEMS
NUMERICAL METHODS IN ENGINEERING
CFD FOR NUCLEAR ENGINEERING
ADVANCED NUMERICAL METHODS FOR COUPLED PROBLEMS WITH APPLICATION TO LIVING SYSTEMS
SCIENTIFIC COMPUTING TOOLS FOR ADVANCED MATHEMATICAL MODELLING



Computational classes are very useful!

in general

educational resources for undergraduate physics education through integration of computation across its curriculum.

http://www.gopicup.org/ [Caballero et al. The Physics Teacher 57.6 (2019): 397-399.]

in plasma physics

ZPIC educational code suite, a new initiative to foster training in plasma physics using computer simulations

https://github.com/ricardo-fonseca/zpic

[Fonseca et al. APS Division of Plasma Physics Meeting Abstracts. Vol. 2020. 2020.]

in laser-plasma

PowerLaPs: Erasmus Plus programme for training in both experimental diagnostics and simulation techniques

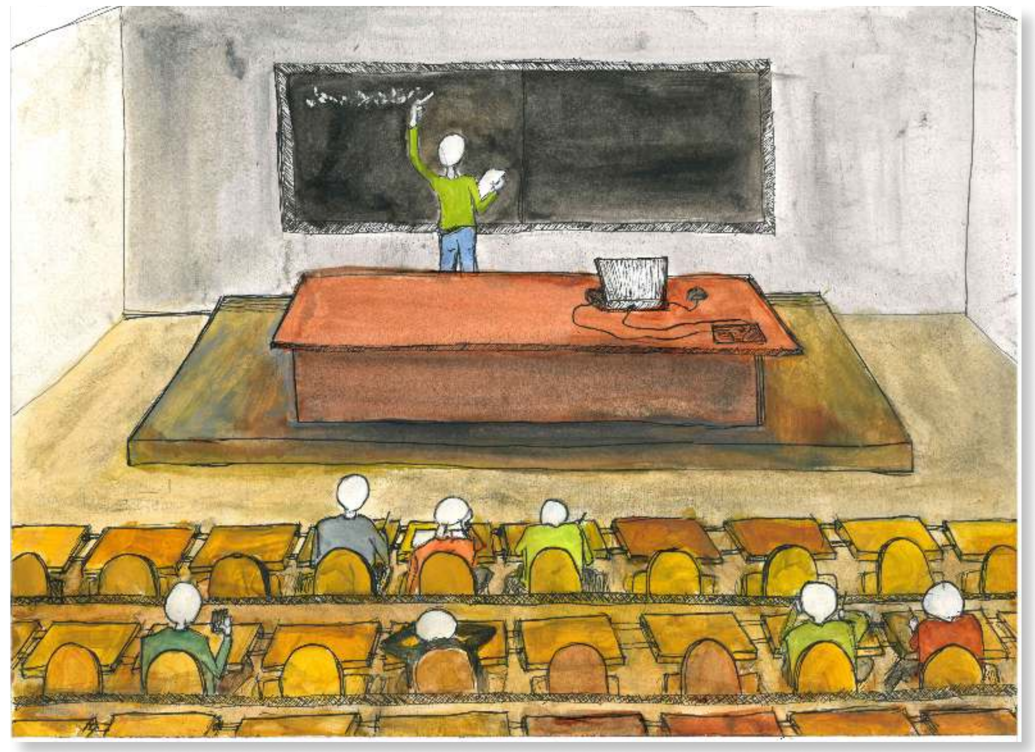
[Pasley et al. High Power Laser Science and Engineering 8 (2020)]

What’s new @ PoliMI

we have introduced 2 different didactic activities explicitely addressing **computational plasma physics** in AY 2020/2021

curricular (but optional)

~ 10 hour conventional classes within the Plasma Physics course



extra-curricular

~20 hour-long hands-on laboratory as an innovative teaching action

using python + Smilei!

Computational plasmas | classes

main classes (by prof. Passoni)

part 1
- fundamental plasma parameters
- guiding center theory
- methods for the description of a plasma
- waves in a plasmas
- emission of radiation in a plasma

part 2
- laser-plasma interaction
- magnetically-confined plasmas
- collisions in a plasma
- controlled thermonuclear fusion

numerical topics

~ 10 hours of conventional classes
~ 10 students online + in class

charged particles' motion

Maxwell's equations

particle-in-cell method

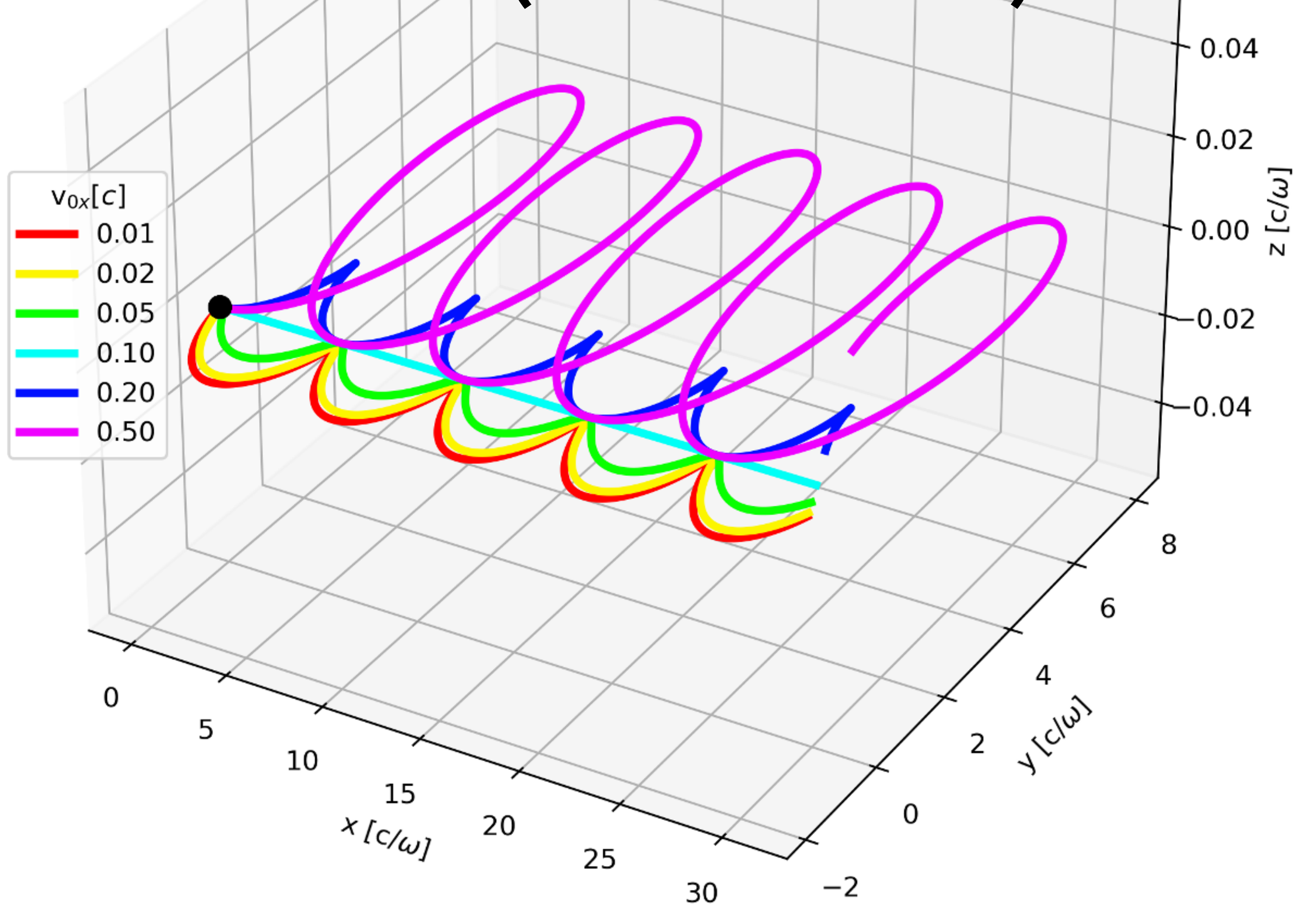
examples

Step 1: charge particles' motion

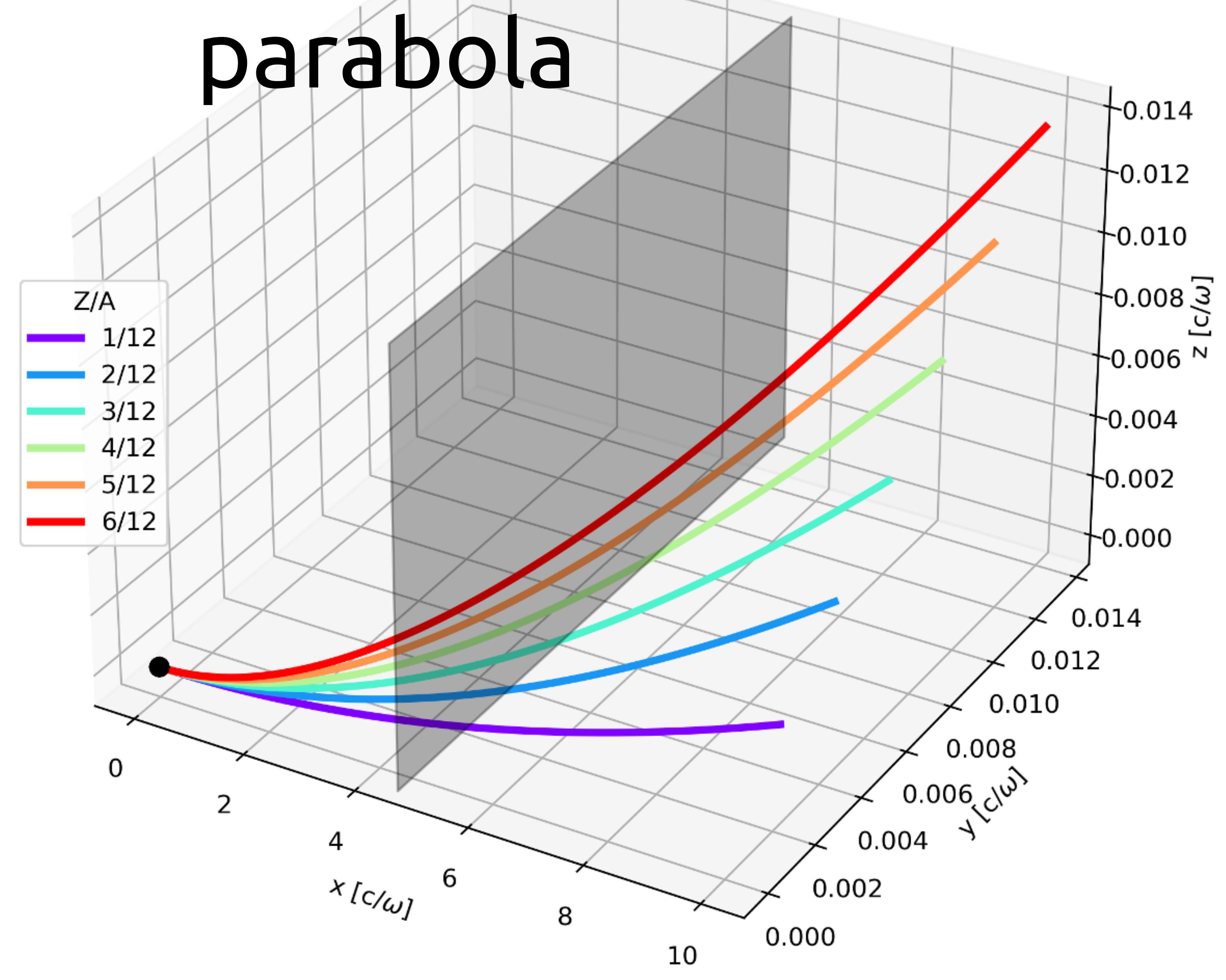
charged particle's equation of motion in assigned EM field ⟶ Boris pusher

simple algorithm:
- students can implement their own version
- visualizations of specific configurations

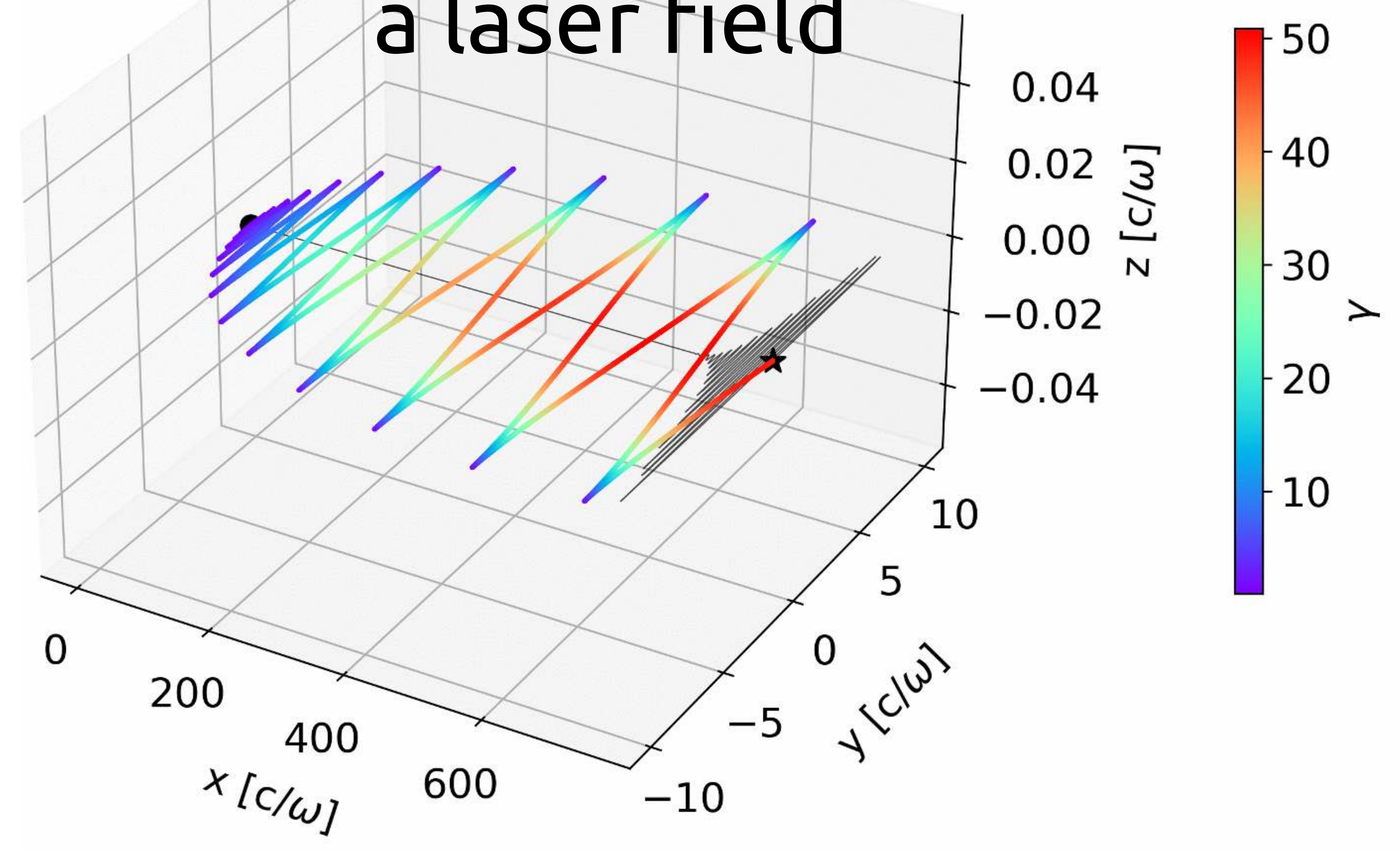
velocity selector (Wien filter)



Thompson parabola

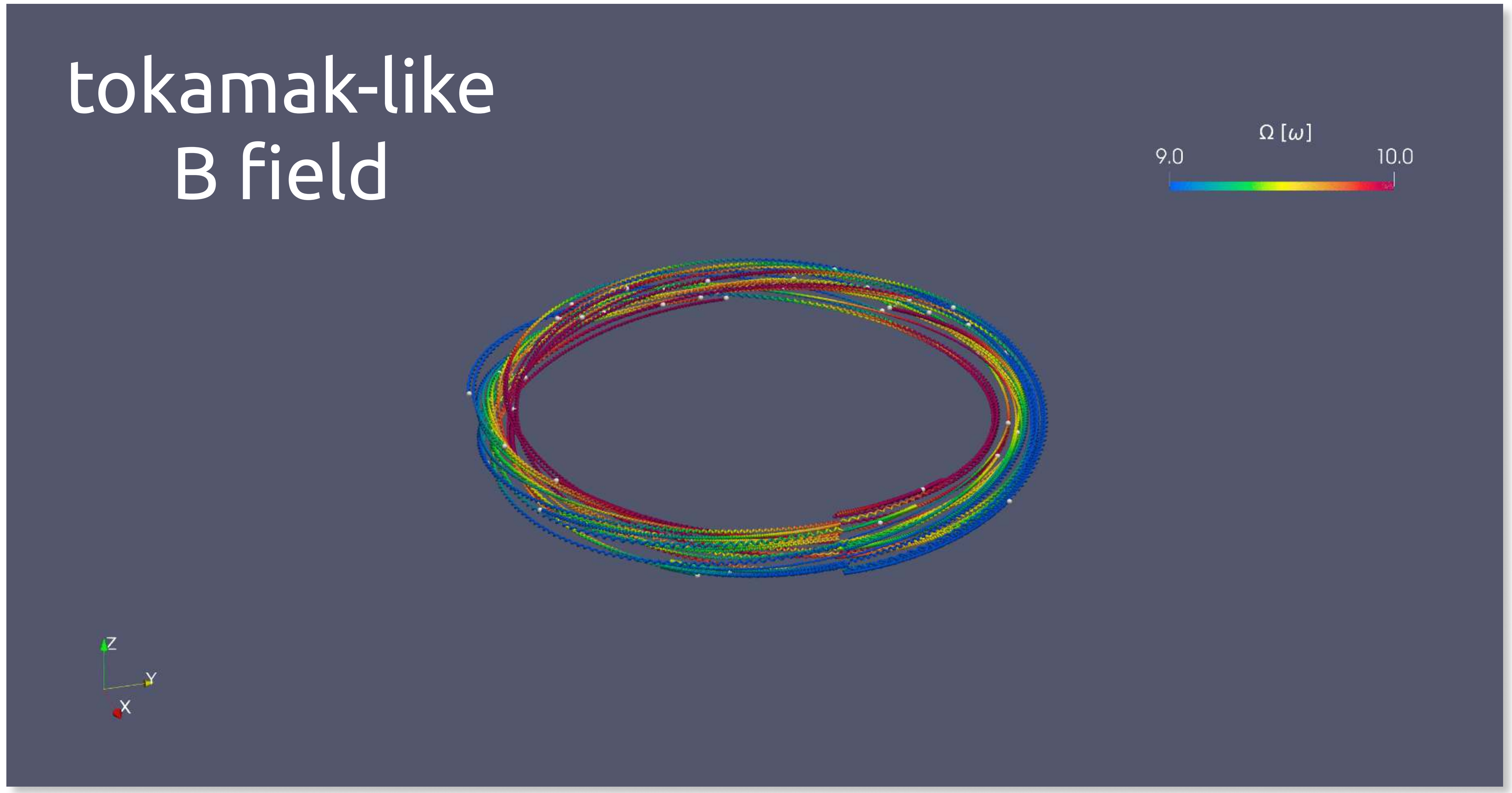


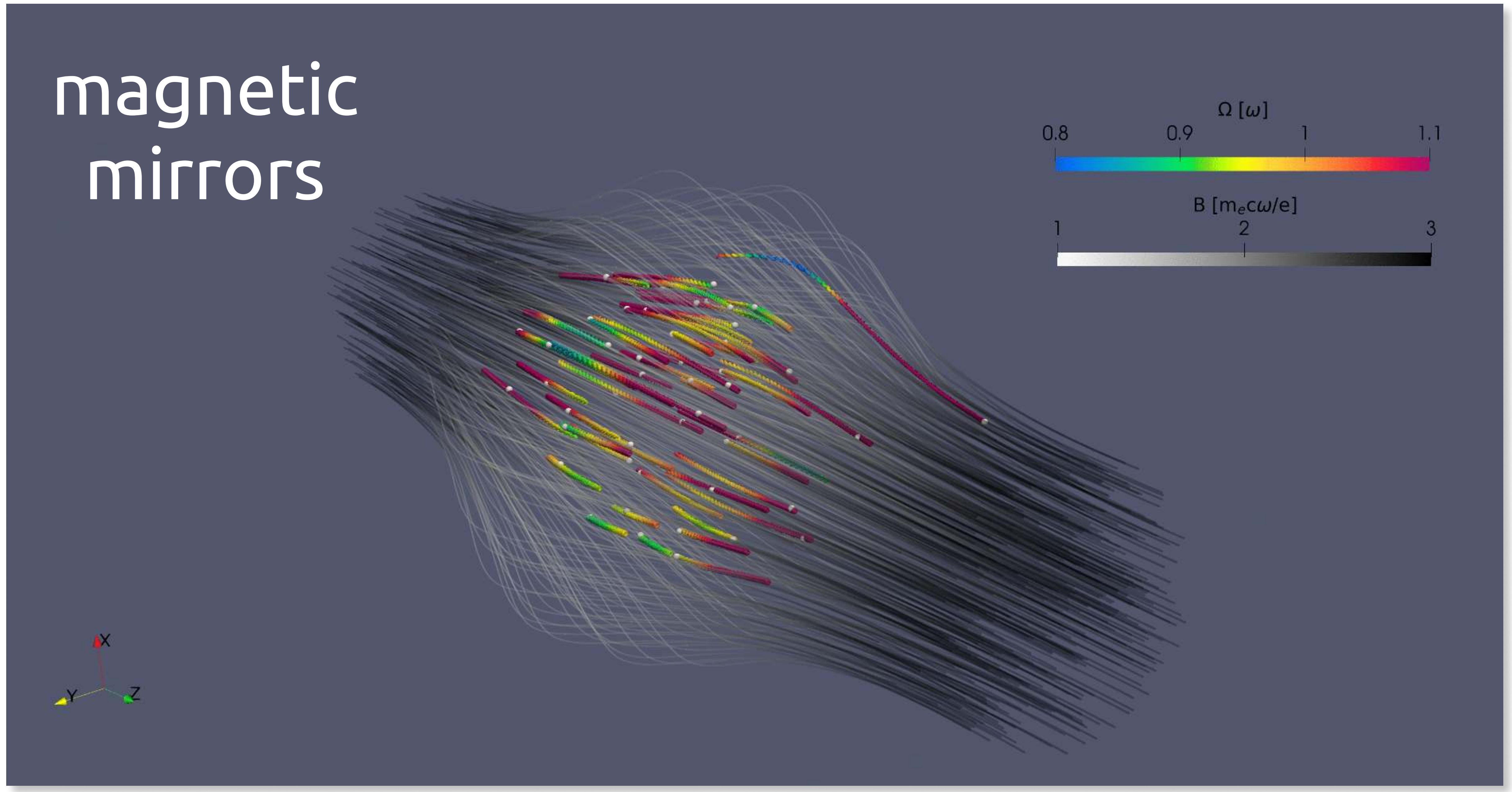
single-electron in a laser field



Step 1: charge particles' motion

examples in complex field configurations





opportunity to familiarize with

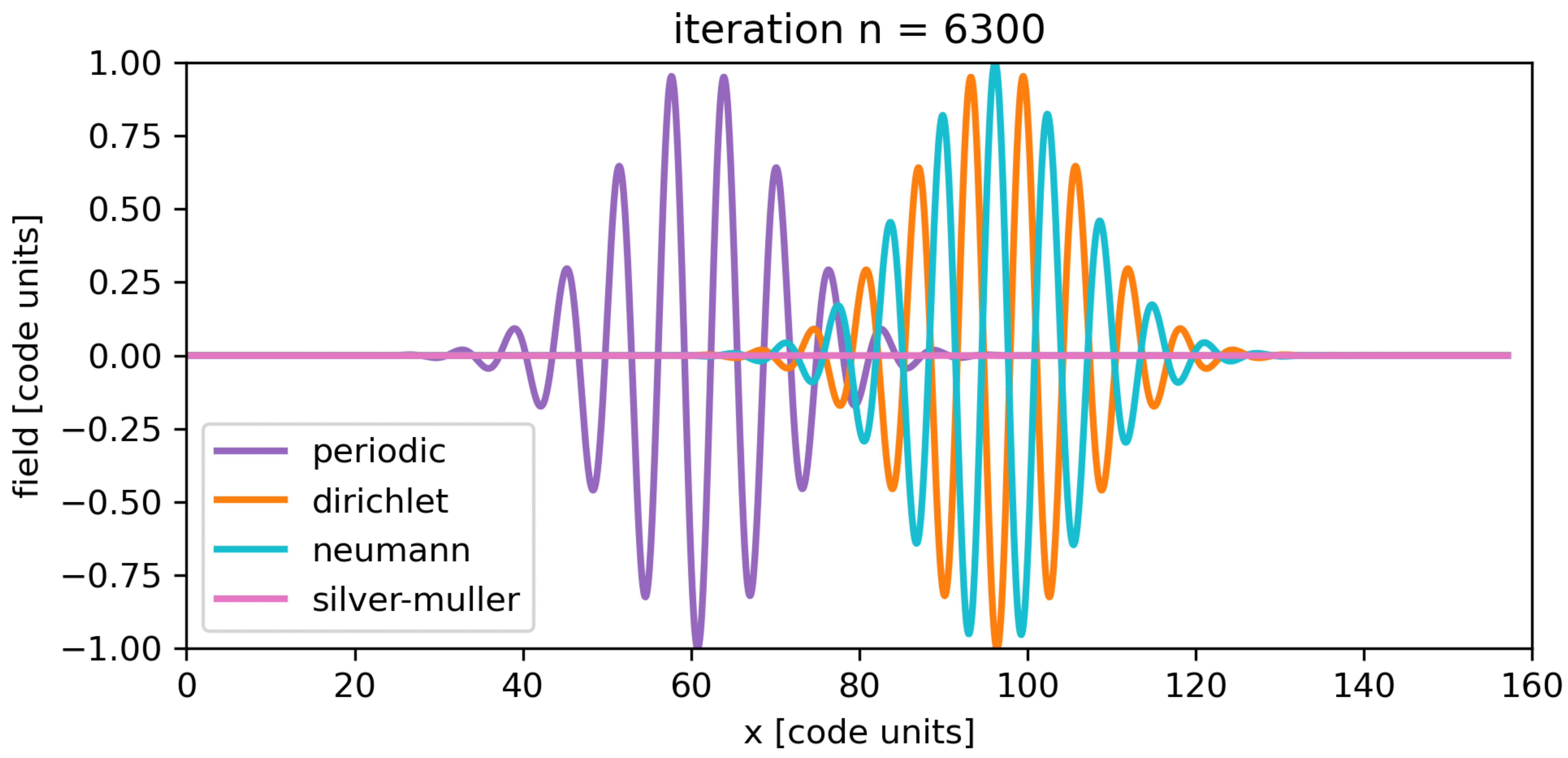
- visualizing 3D particle orbits
- particles' drifts
- relativistic vs. non relativistic
- electron vs. proton
- electron vs. positron

Step 2: Maxwell's equations

1D Maxwell equations with given sources ⟶ FDTD algorithm with Yee grid

simple algorithm:
- students can implement their own version

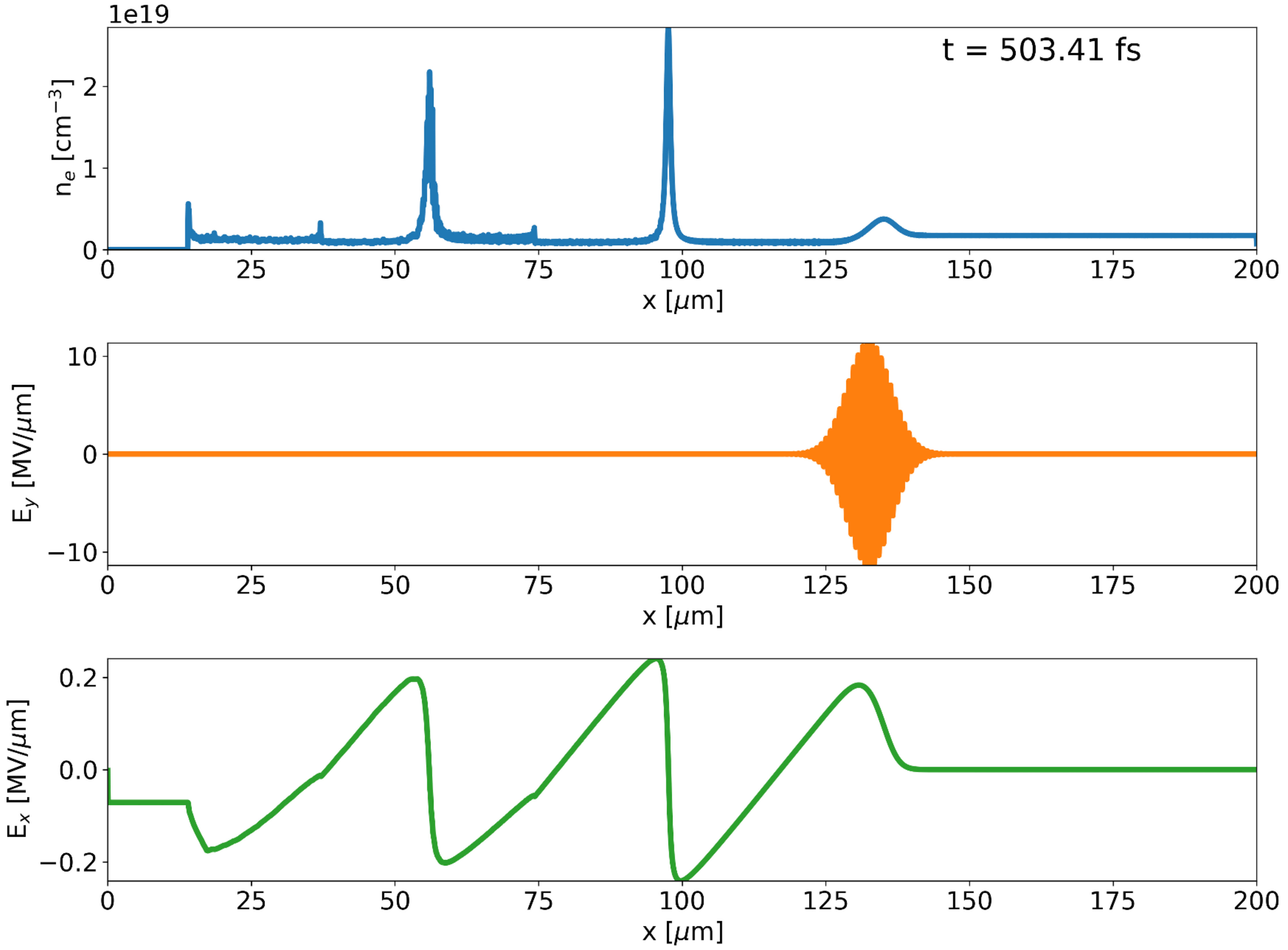
- so far only laser pulse travelling in vacuum with different BCs
- other ideas: simple expressions for the current density J (e.g. linear in E)



Step 3: particle-in-cell method

particle-in-cell method → too complex for the students to code their own version

however there's Smilei !



why Smilei ?

- open-source
- very well documented
- user-friendly
- tutorials online
- opportunity to use a research tool

what we did

- went through references
- went through a simple inputfile
- **compared theory with numerical experiments**

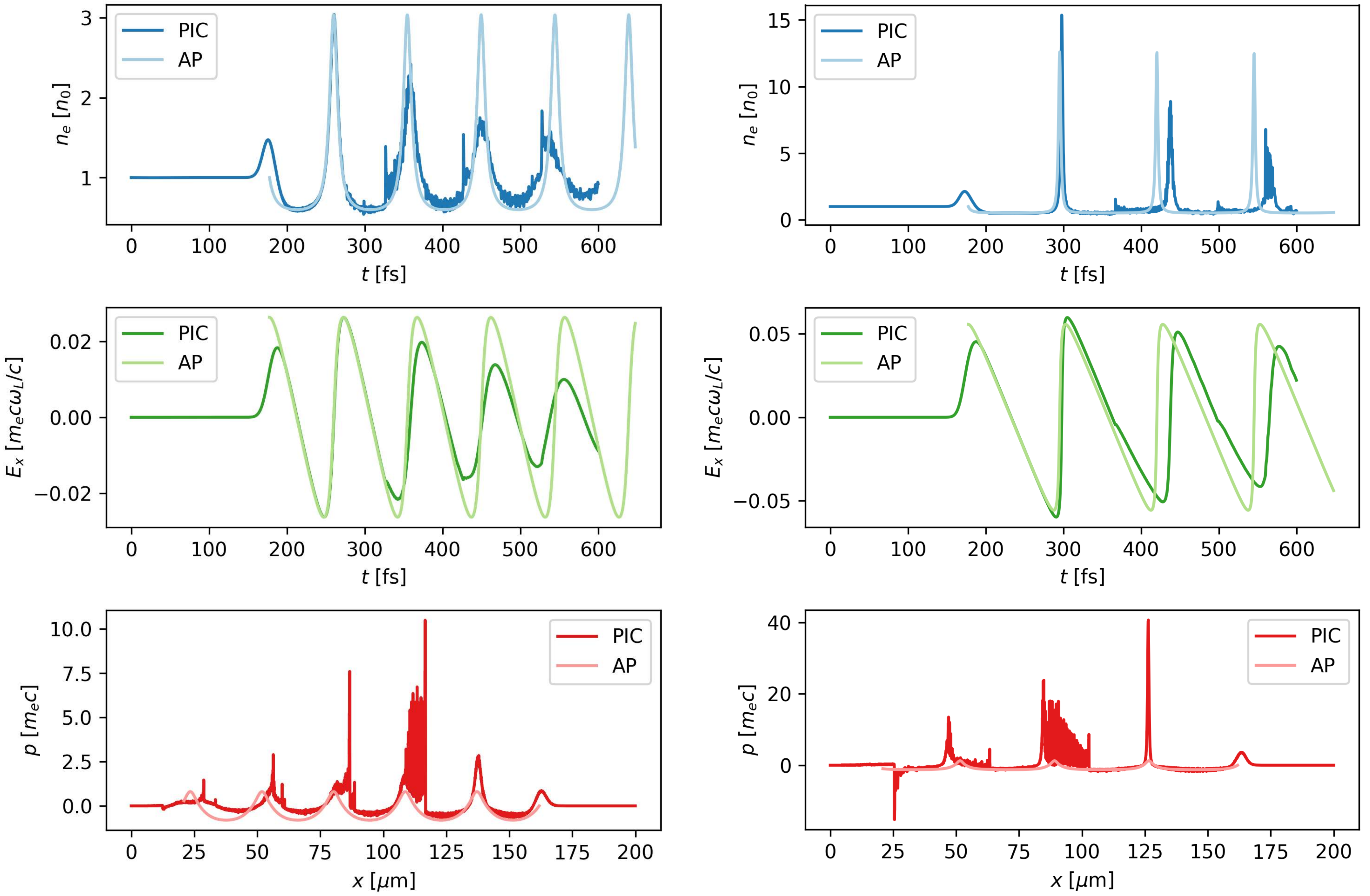
Step 4: examples of Smilei in action

$\tau_L \sim \pi/\omega_p$

$n_{e0} = 0.001 n_c$

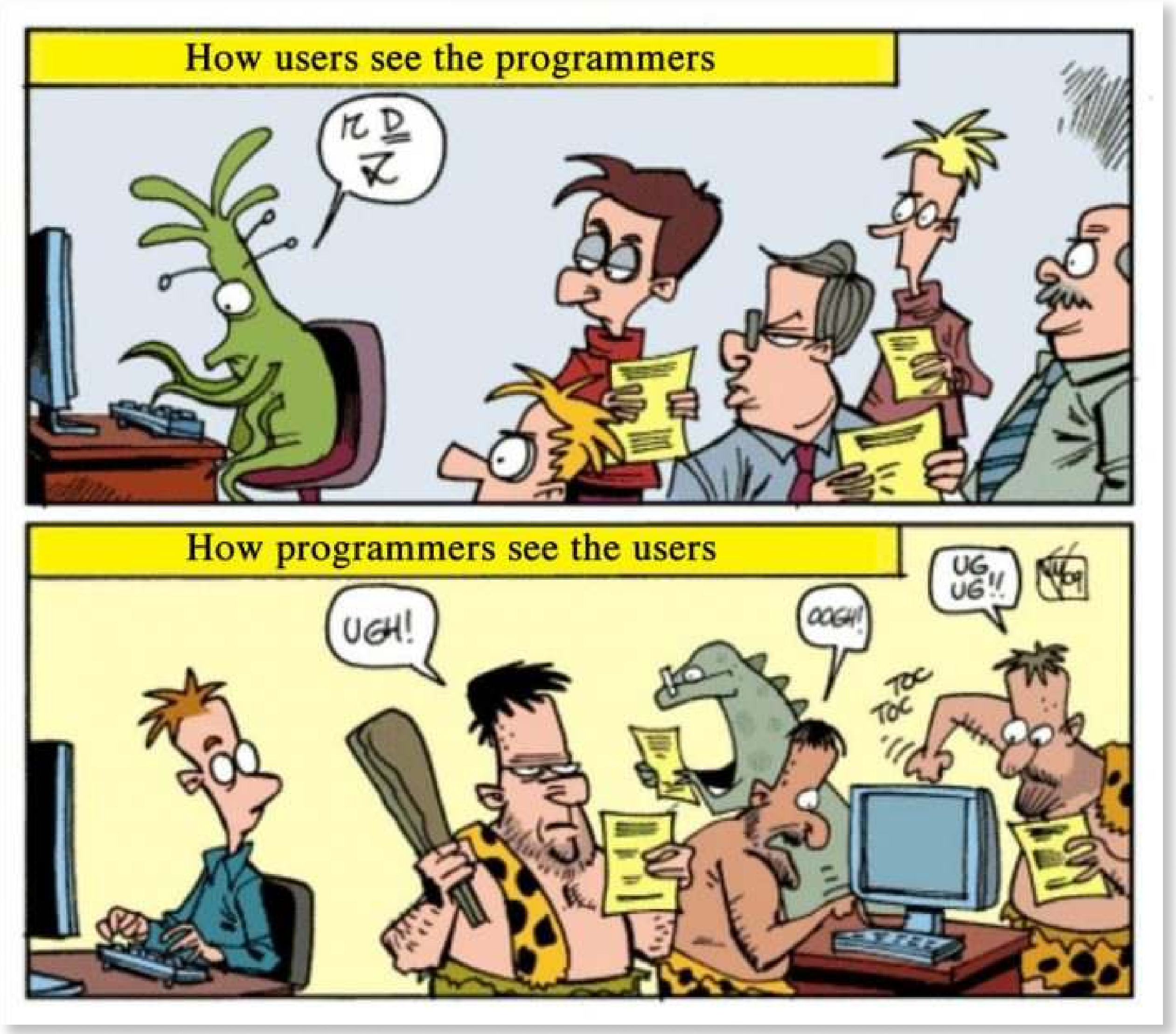
- visualizations of different regimes of interaction
  - under-, near-, over-critical
- review and “test” of wave propagation in a plasma
  - linear theory
  - relativistic cold theory
  - direct comparison between Akhiezer-Polovin longitudinal modes and 1D PIC simulations
  - wakefield & wavebreaking

$a_0 = 2, u_m = 0.67, \beta_p = 0.999$ | $a_0 = 4, u_m = 0.92, \beta_p = 0.999$



Computational plasmas | hands-on lab

~ 20 hours of active work
+ work at home if necessary
no grade + official badge



2 pillars for 2 goals

“user”

learn how to use Smilei)

- benchmarking their own code
- simulating more complex scenarios

“developer”

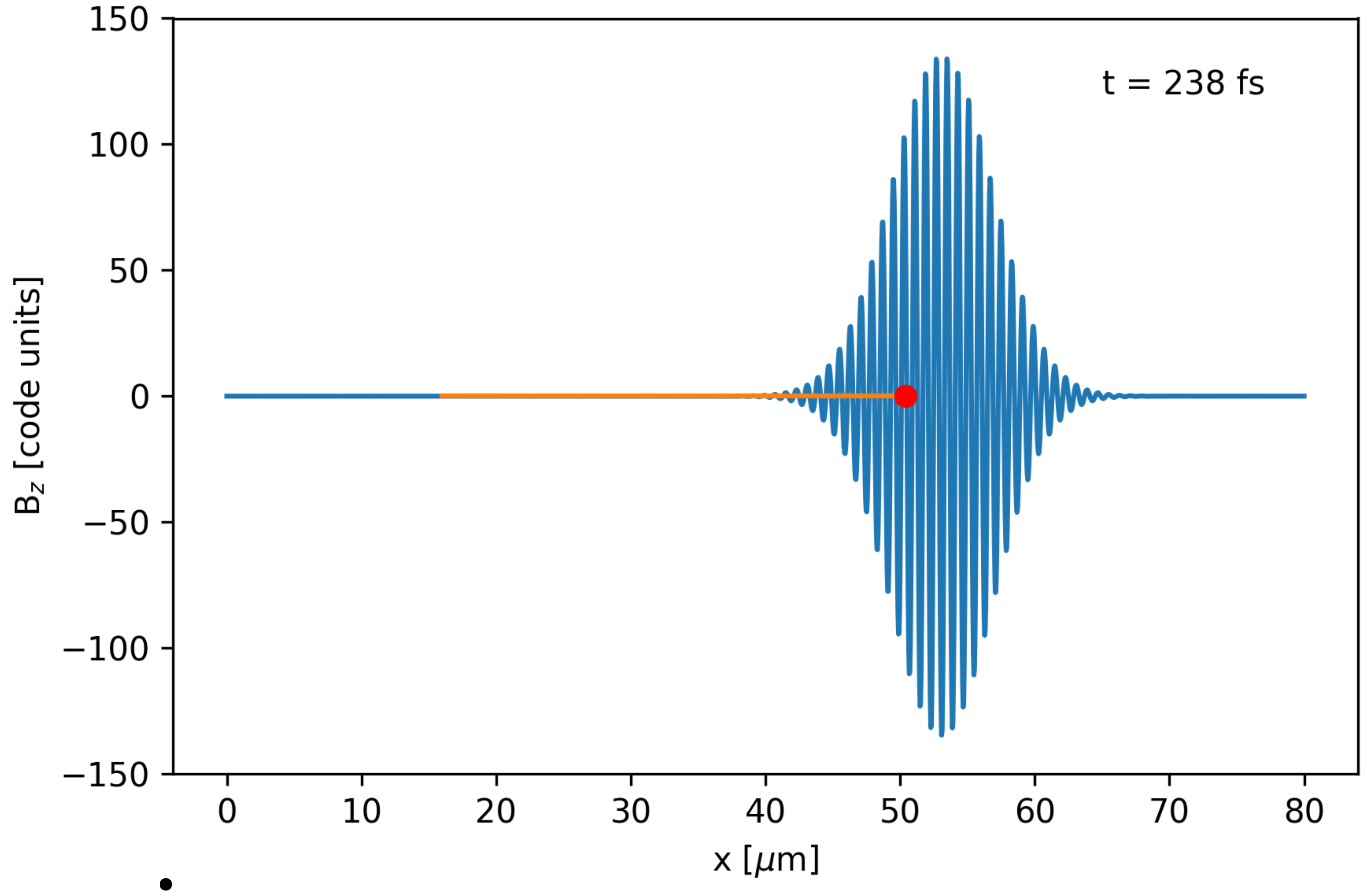
code a basic 1D PIC code

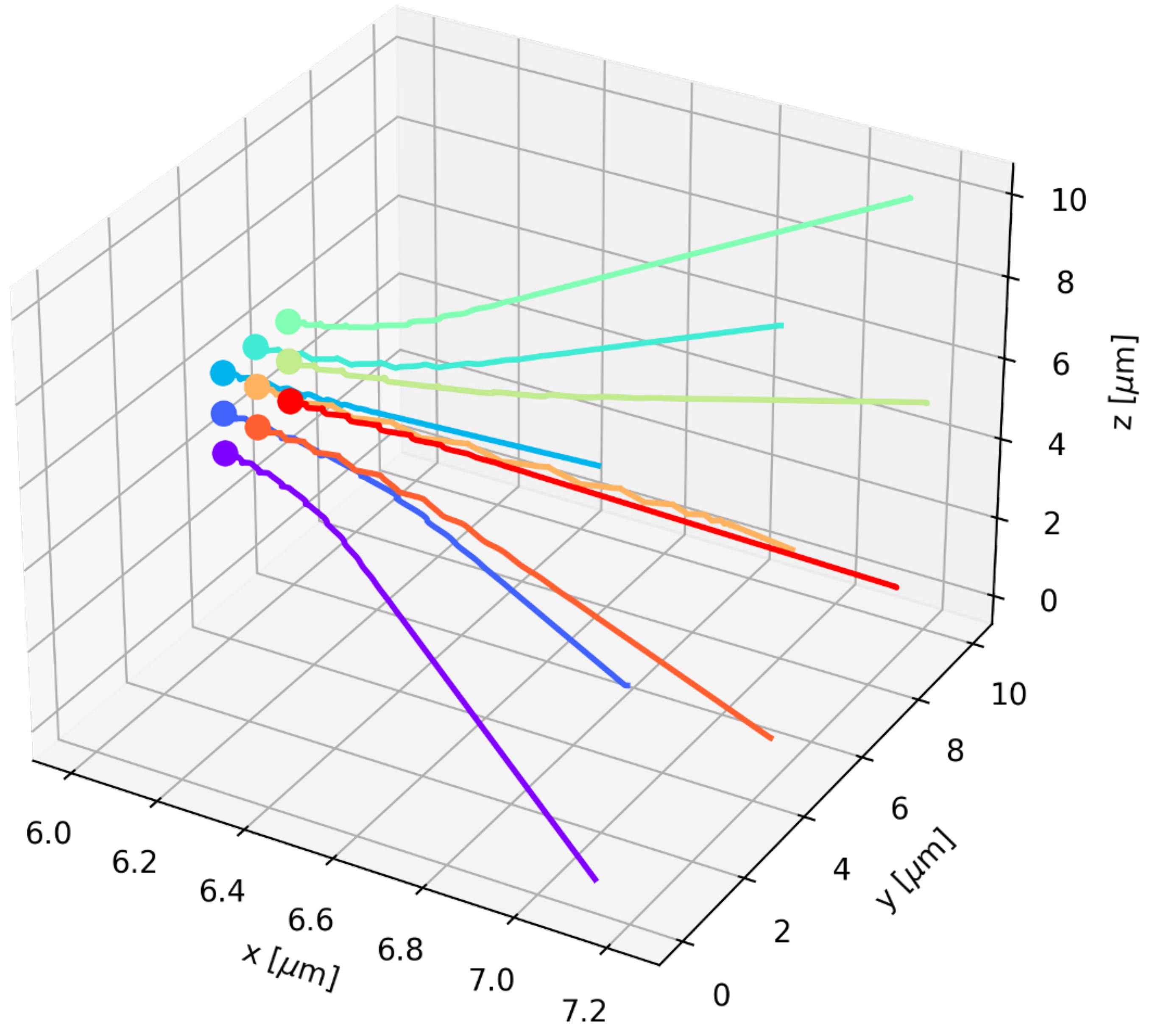
- step-by-step “guide” in python
- students chose to use Matlab or python

Computational plasmas | hands-on lab

“user” work plan

how do we use Smilei ?





- installation & compilation
- starting point = empty inputfile
  + plot script
- progressively more complex scenarios:
  - 1D laser propagation in vacuum
  - 1D thermal plasma
  - 1D laser-plasma interaction
  - 1D laser wakefield generation
  - 1D two-stream instability
  - 2D & 3D laser-electron interaction

note: parameters and simulations all within the ultra-short laser-plasma interaction domain for now, but wishing to expand!

Computational plasmas | hands-on lab

“developer”: work organized in subsequent tasks

1. define the unit quantities
2. create the space & time discretizations
3. print the main parameters
4. define the EM field structure
5. initialize the EM field to a laser pulse
6. write the Maxwell solver
7. write the time loop
8. test laser progation in vacuum
9. add periodic boundary conditions
10. compute the total field energy
11. define the plasma species structure
12. test your species without particles
13. add particles to the species
14. test your species with few particles
15. number density of a uniform plasma
16. initialize particles positions and weights
17. test the initialization of particles positions
18. initialize particles momenta
19. test the initialization of particles momenta
20. test the overall initialization procedure
21. write a routine for charge deposition
22. add new initial density profiles
23. test the charge deposition
24. advance the (test) particles positions
25. periodic boundary conditions for the particles
26. test the (test) particles motion
27. check the charge density upon motion
28. compute the kinetic energy of the species
29. test the (test) particles kinetic energy
30. implement the field gathering
31. implement the Boris pusher
32. add the pusher to the time loop
33. test the particle pusher with constant E
34. test the particle pusher with constant B
35. implement the current density deposition
36. add the deposition to the time loop
37. test the current deposition
38. test the code

the students use Smilei) to test and debug their code

- some degree of autonomy thanks to the documentation & source code
- positive feedback in being able to use a research tool
- happi also very useful!

Computational plasmas | hands-on lab

last year 2020/2021

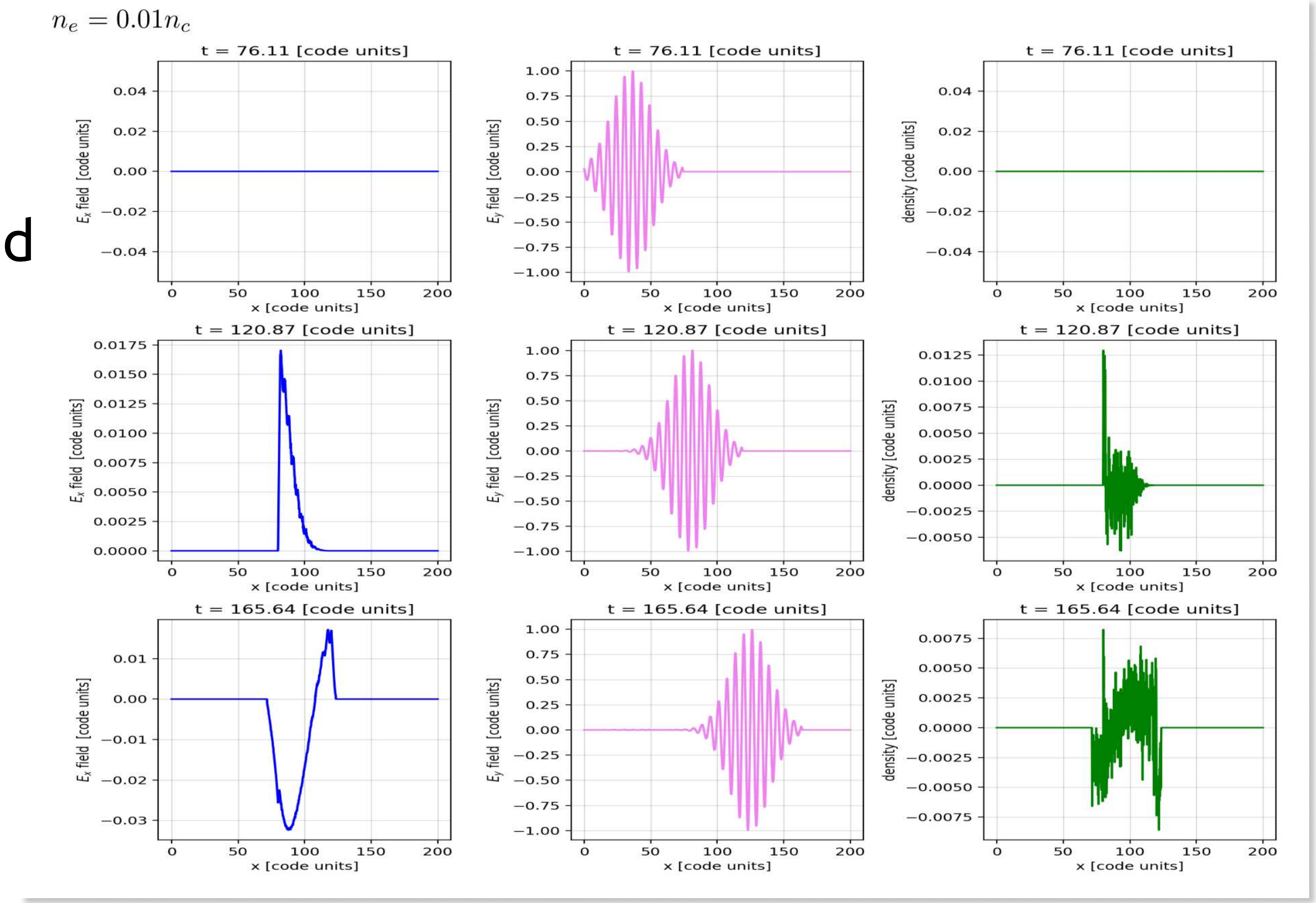
- online
- the students were able to get to an alpha version of their code
- 10 students - only 2 made it to the end

this year 2021/2022

- hybrid: presence + online
- 12 students enrolled
- starts next week

(unfortunately some students do not have a “strong” computer science background and are daunted by coding especially in python)

example from a student



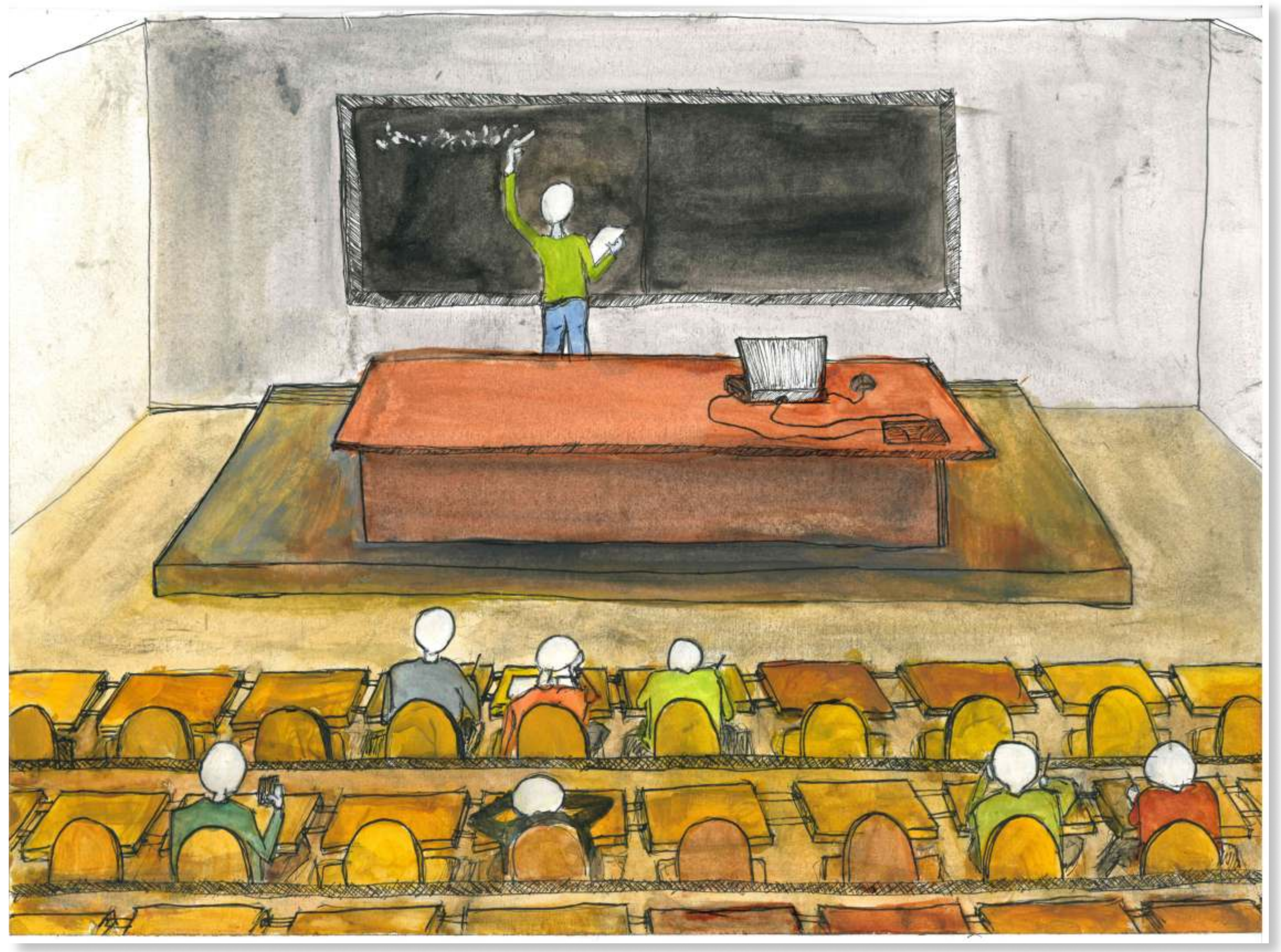
Concluding remarks

- both curricular and extra-curricular activities have attracted the attention of ~10 students of the ~50 attending the Plasma Physics course

- feedback was positive & constructive especially because the students enjoy “practical” activities & visualizing the physics

- the students need to be guided step-by-step not to be disoriented (e.g. by giving them a basic input file + plot script)

- **Smilei) is a very effective tool to teach computational plasma physics!**



Perspectives, ideas, etc.

ideas for Smilei:

- including in the tutorials benchmarks with analytic theory?
- other topics for tutorials? maybe more educational-oriented? or more textbook-insipired?
  - parametric instabilities
  - astrophysical plasmas
  - emission of radiation raction vs. Lienard-Wiechert theory

open critical points

- online work is far from optimal
- very few non-male participants
- why “only” 10 out of 50 students?
- code development in groups?
- explore other physics than laser-plasma interaction?
- improve code development to make it an opportunity to acquire coding skills?

any ideas, comments, recommendations & suggestions would be very welcome!

Thank you for your time!