Laser-plasma acceleration beyond wavebreaking

Bernardo Malaca[1],

Jorge Vieira[1], John Palastro[2]

bernardo.malaca@tecnico.ulisboa.pt

[1]GoLP / Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico, Lisbon, Portugal

[2] Laboratory for Laser Energetics, University of Rochester, Rochester, US

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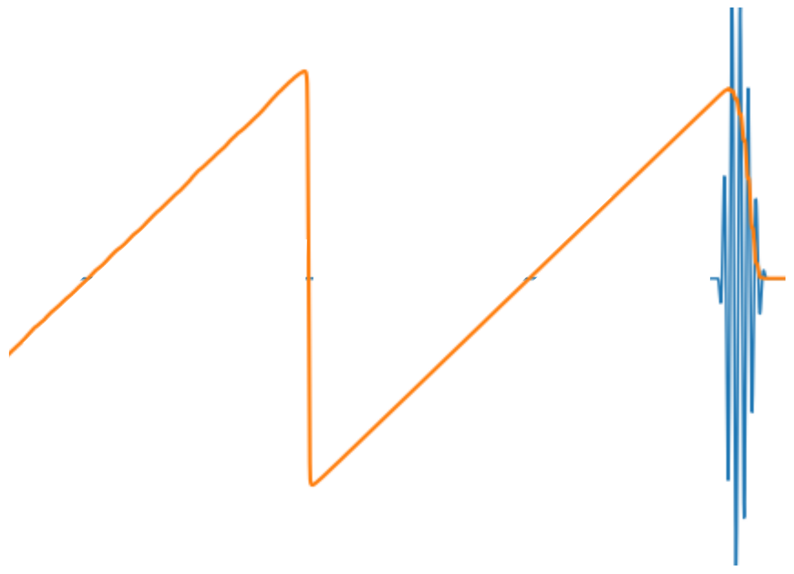
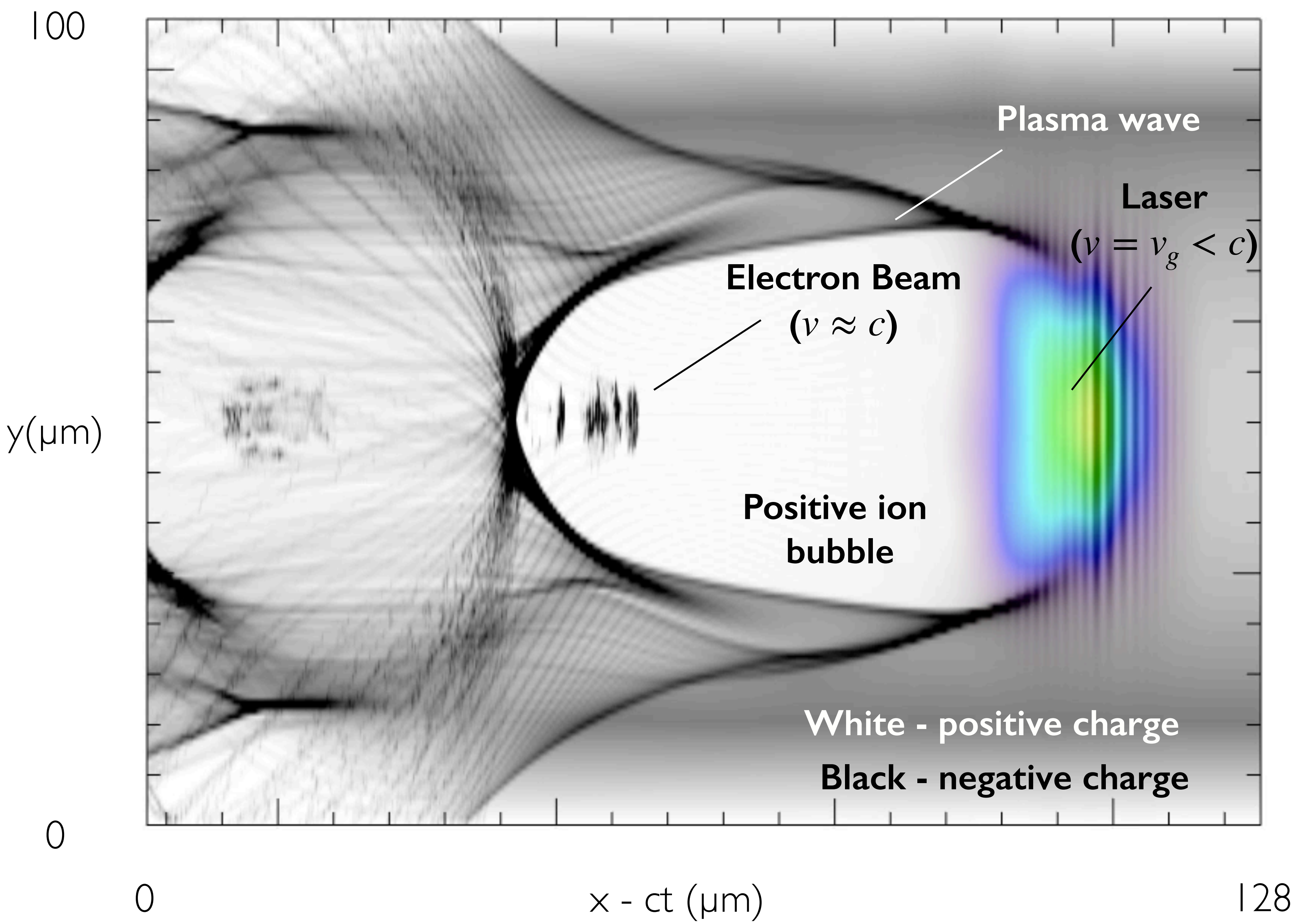


Laser Wakefield Acceleration (LWFA)



Acceleration Properties

- Gaussian intense laser pulse
- Semi-spherical plasma wave

Experimental results

- BELLA: 8 GeV in 20 cm of plasma
- 3 orders of magnitude above std. accelerators

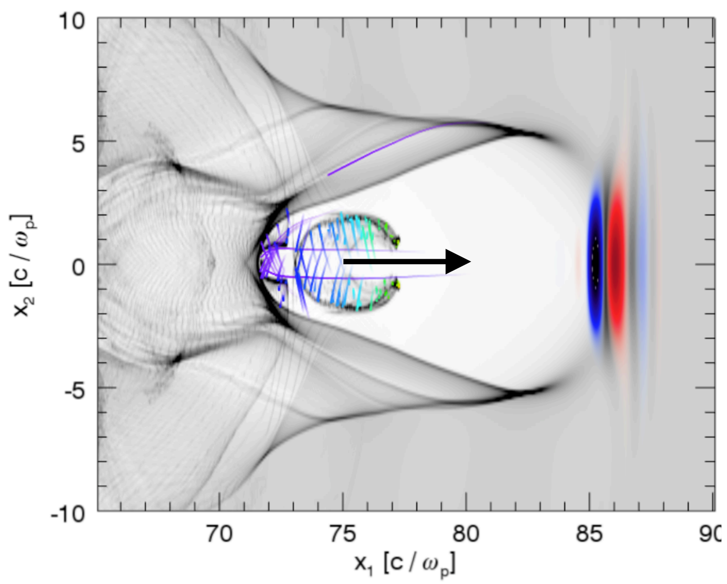
Final properties of e-beam

- Efficiency: ~1%
- Charge: 10s of pC
- Energy spread: ~10%

Can we get higher gradients, higher energies, higher efficiencies?

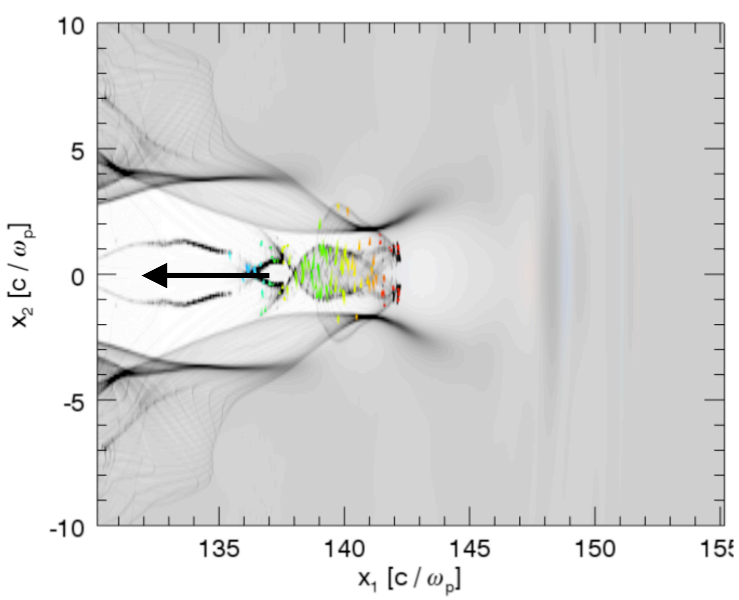
Dephasing is the main bottleneck

Laser Wakefield accelerators are limited by dephasing



In the beginning electrons are accelerated

Ion bubble in front



After some time electrons are decelerated

Ion bubble at the back

What would be the perfect laser?

Laser velocity

If laser goes at c dephasing cannot happen (the ion bubble is always in front)

Peak intensity

Constant and along a line

Beyond the limits of LWFA

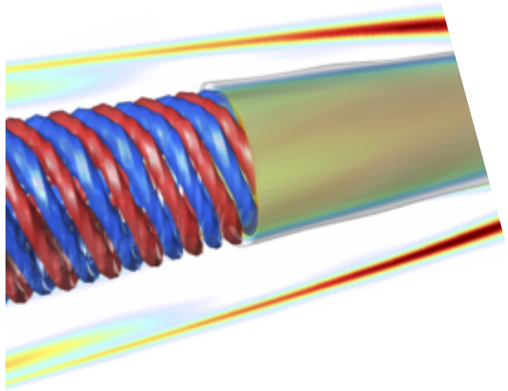
Unique property of plasma : Flexibility

RF cavities

- Solid (Metal)
- Fixed plasma acceleration structure

Plasma

- Free particles
- Flexible plasma acceleration structure

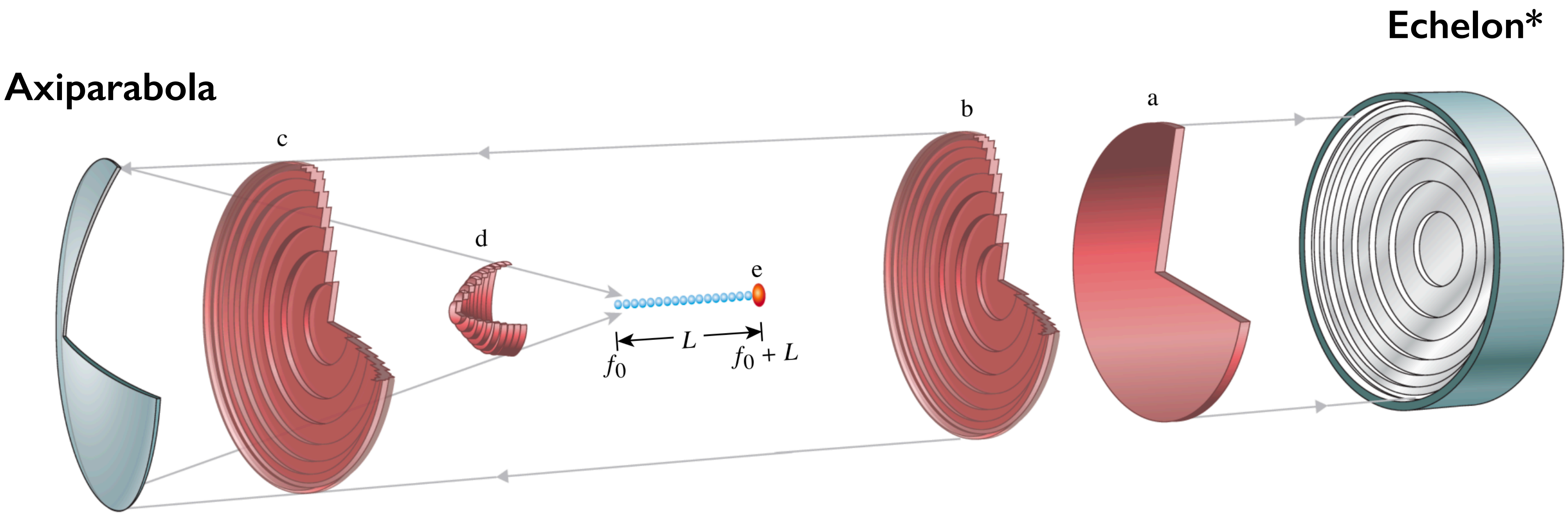


Manipulating laser internal structure

Using a gaussian driver gives us **one** degree of freedom:
the total laser energy

There are hidden degrees of freedom in the internal structure of the laser
(the laser focal velocity can be modified)
How?

Experimentally controlling laser focal speed



Setup

(a) The laser pulse first reflects off of a stepped echelon, which imparts the temporal delay required for a predetermined focal velocity.

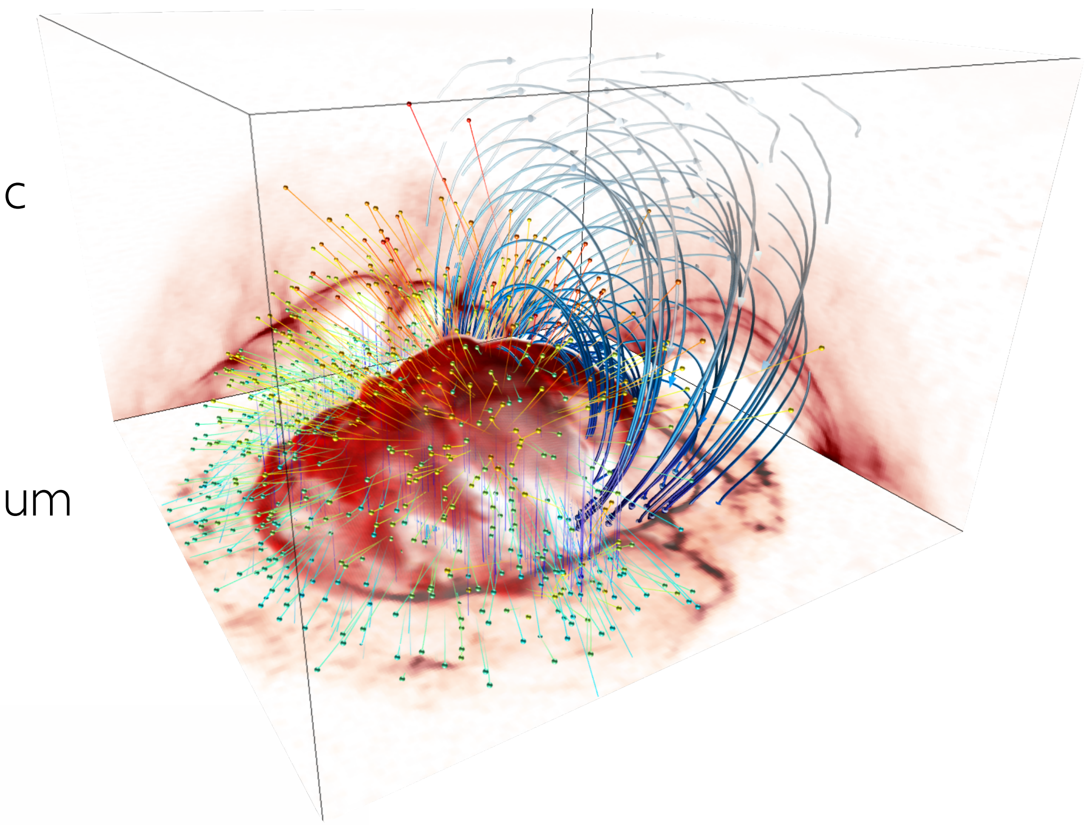
(c),(d) After reflecting from the echelon, the pulse encounters the axiparabola, which focuses different rings in the near field to different axial locations, stretching the region over which the pulse can sustain a high intensity from the initial focus

(e) The pulse drives a wakefield at the desired focal velocity

* J. Palastro *et al*, PRL **124** (**2020**)

Particle-In-Cell simulation with OSIRIS 4.0

Osiris 4.0



osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST

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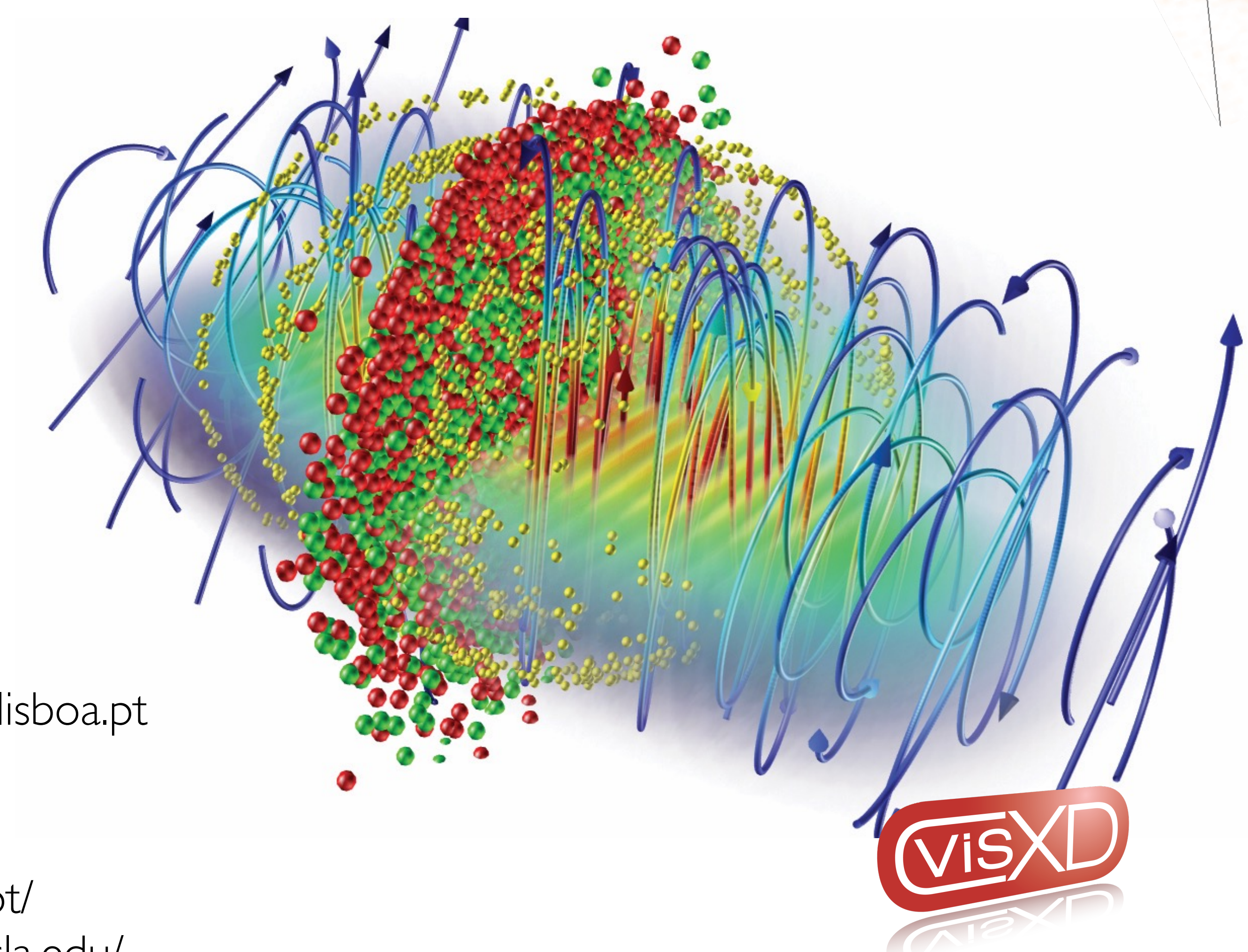


code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU & Xeon Phi support
- **Flying Focus Module**

Ricardo Fonseca
ricardo.fonseca@tecnico.ulisboa.pt
Frank Tsung
tsung@physics.ucla.edu

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

Superluminal "laser" propagation in 1D cold plasma

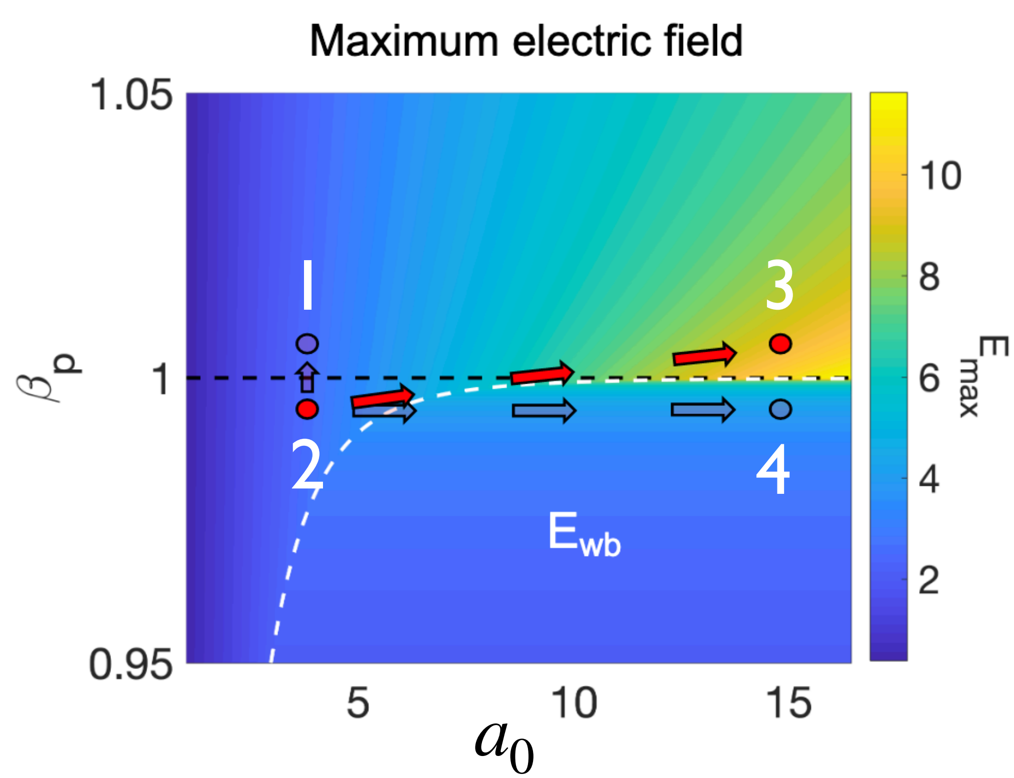
Theory

Below wave breaking thresholds (low intensity):

Plasma sustains similar electric fields for sub and superluminal pulses

Beyond wave breaking thresholds (high intensity):

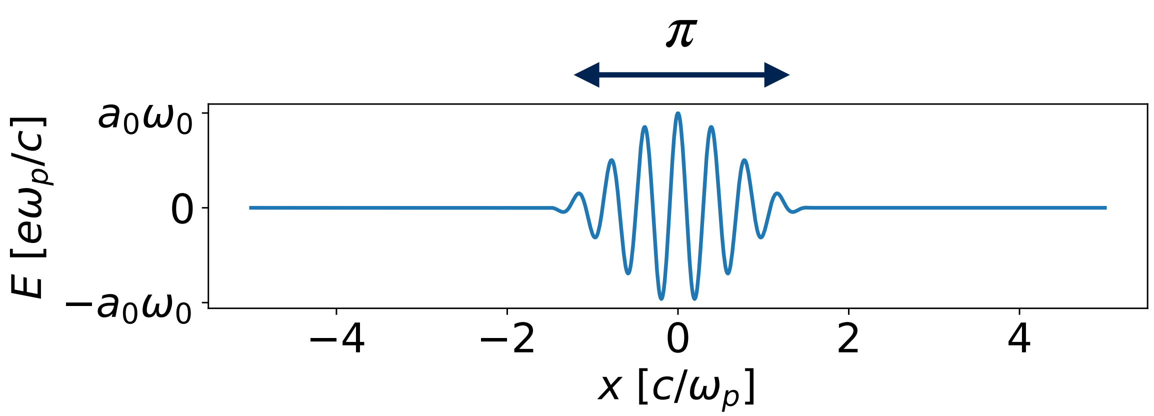
Plasma sustains much higher electric fields for superluminal pulses



Simulation

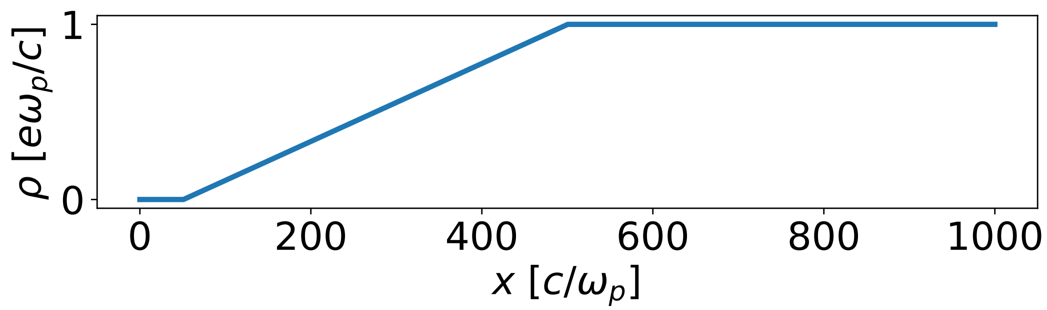
Non-evolving external driver

$$E(x,t) = a_0\omega_0 \cos(kx - \omega_0 t)\, f(x - \beta_p t)$$



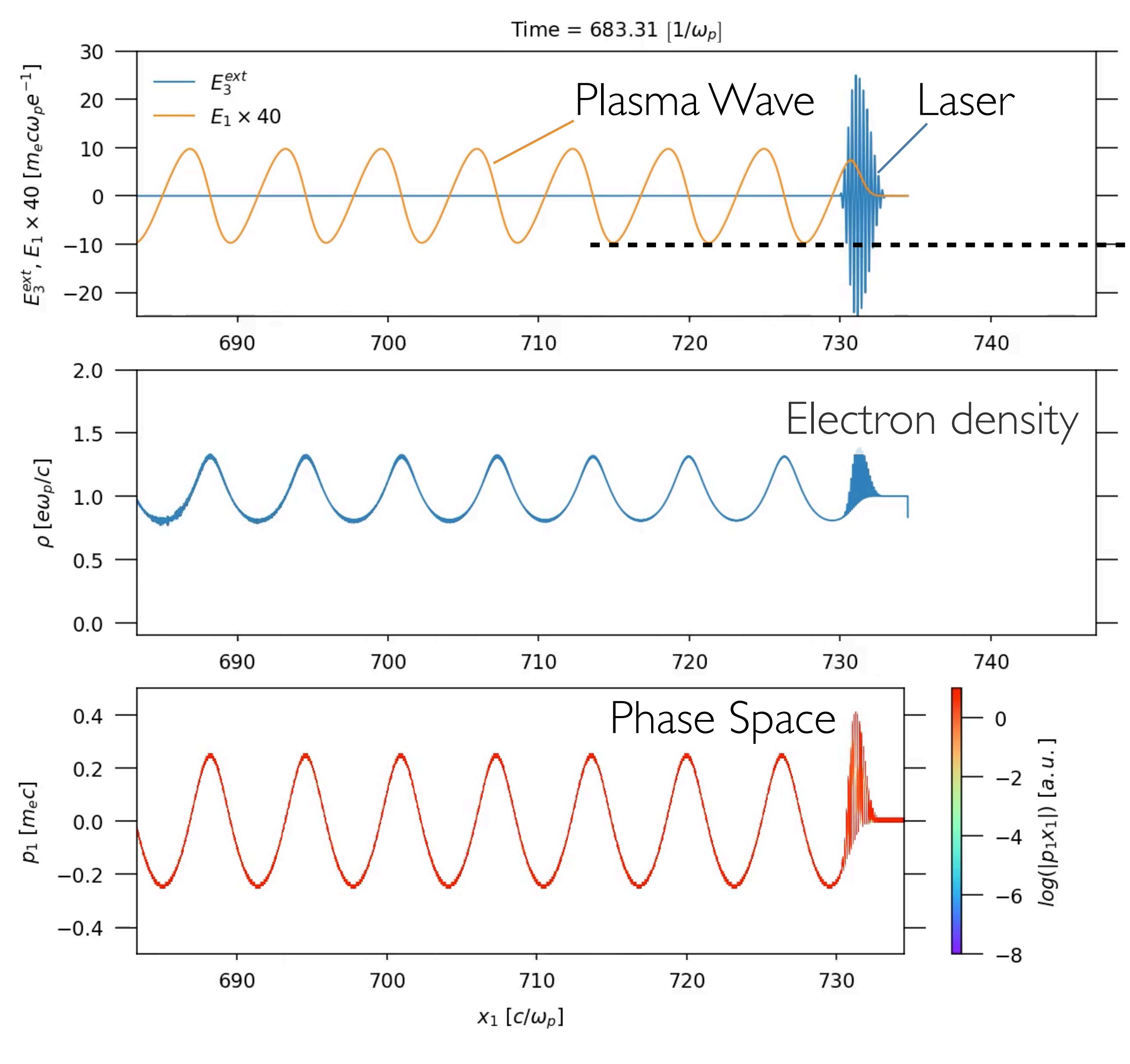
Plasma density ramp

Avoids non-physical electron trapping induced by a sharp boundary

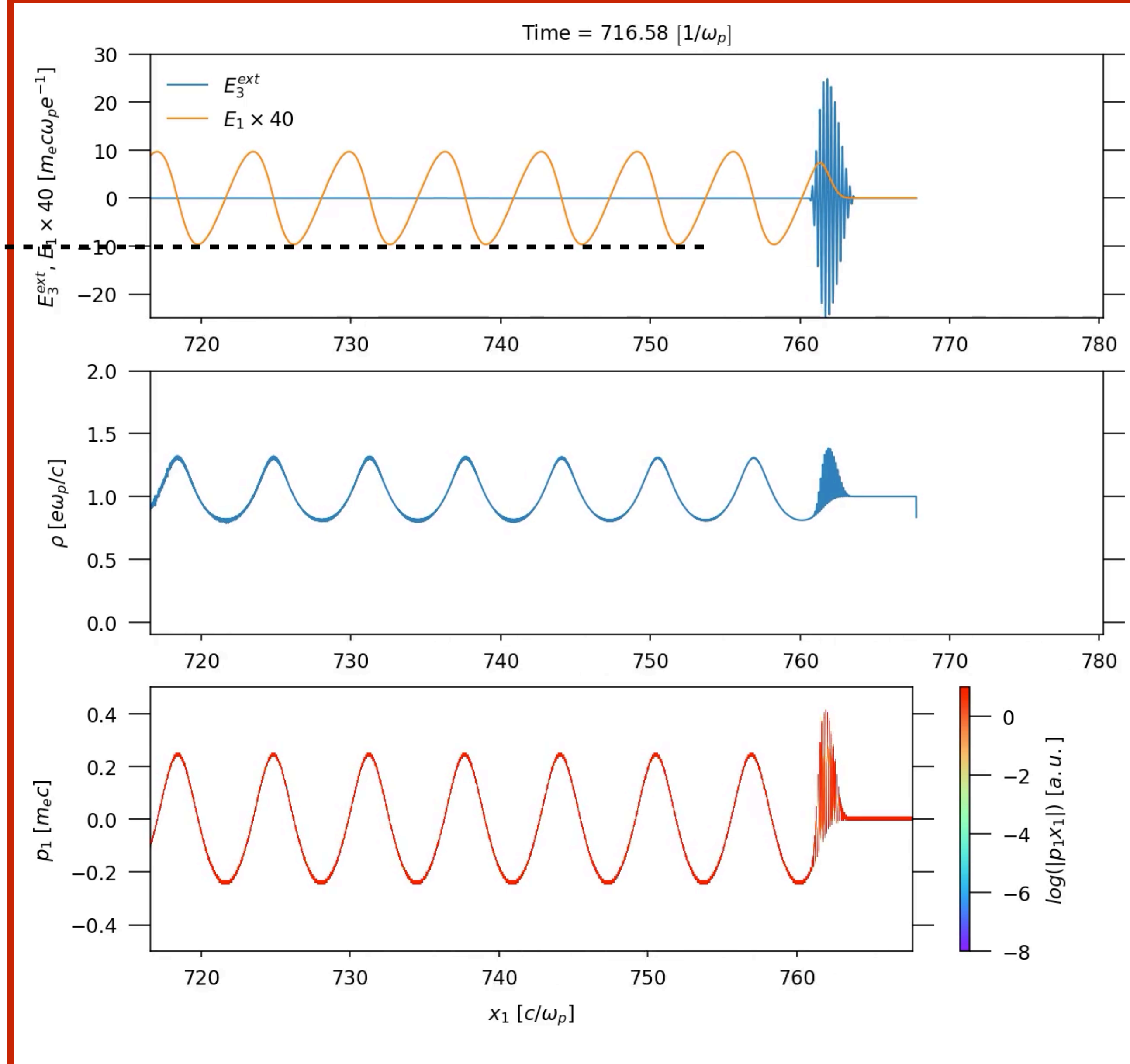


Below wave breaking thresholds: a_0=2

Subluminal $(v_g = 0.99)$



Superluminal $(v_g = 1.01)$



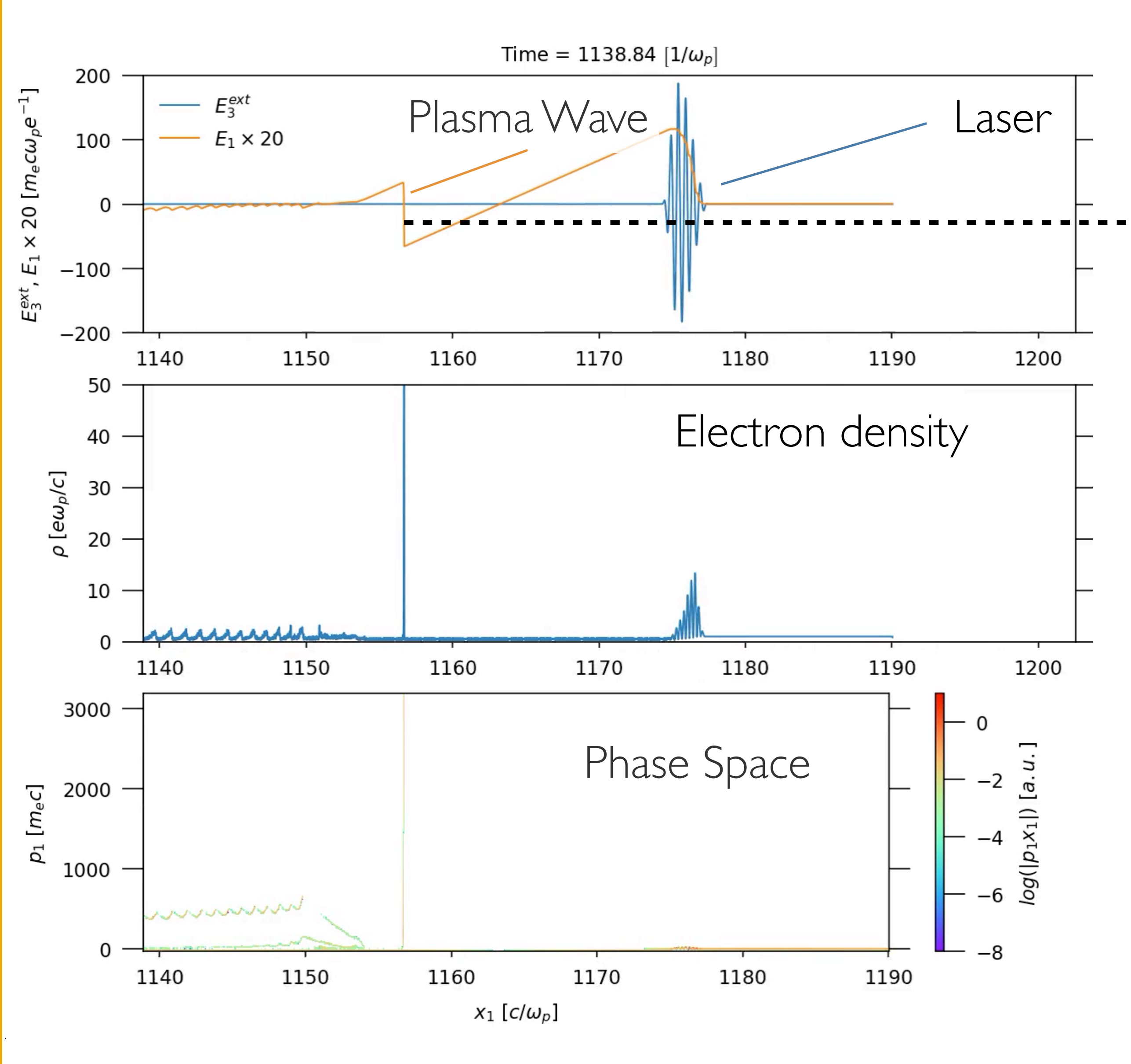
Linear response of the system: there is no electron injection in the wave

(the amplitude of the wave does not depend on the laser focal velocity)

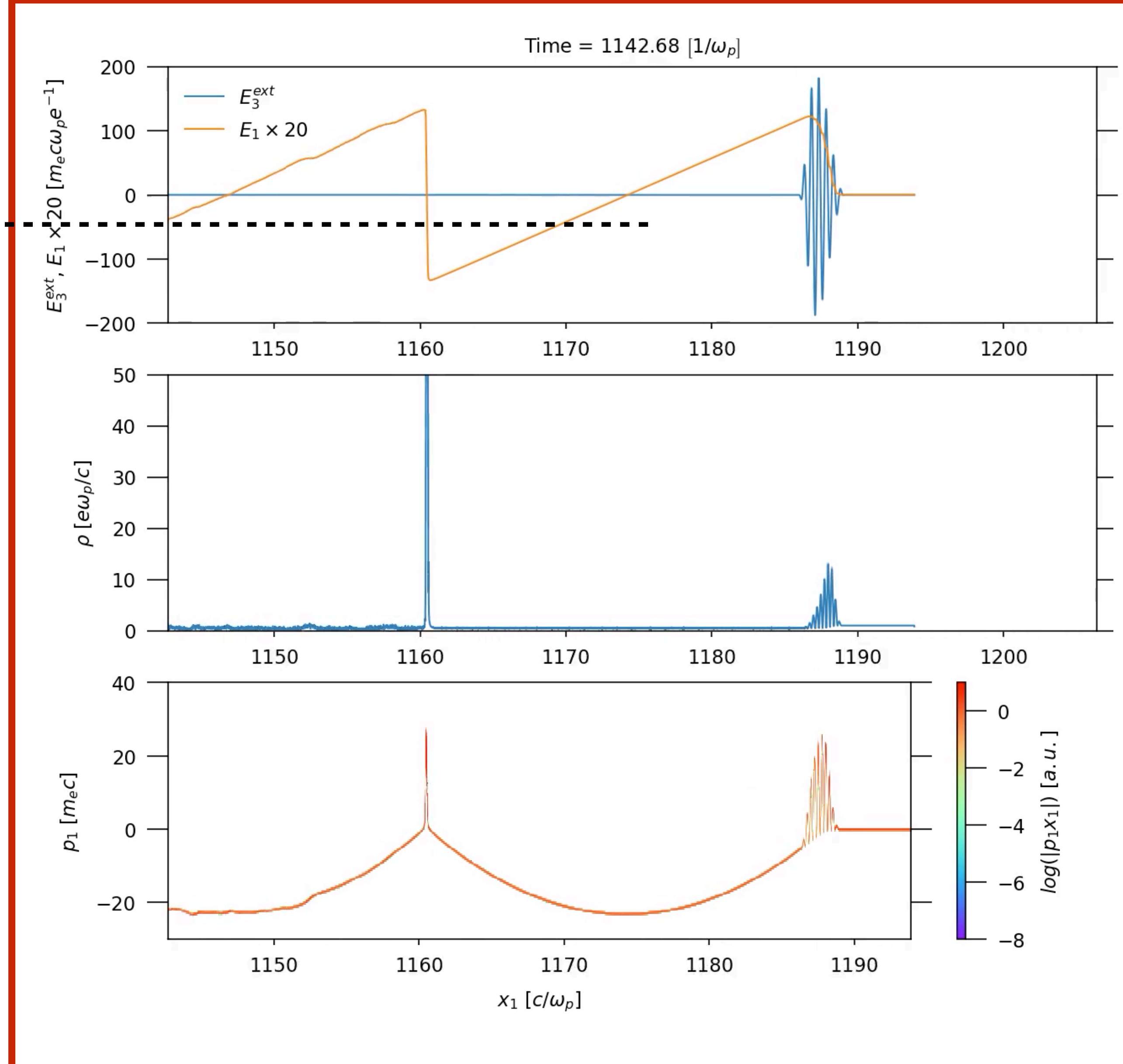
* J. Palastro, B. Malaca, J.Vieira et al *(submitted)* (**2020**)

Beyond wave breaking thresholds: a_0=15

Subluminal ($v_g = 0.99$)



Superluminal ($v_g = 1.01$)

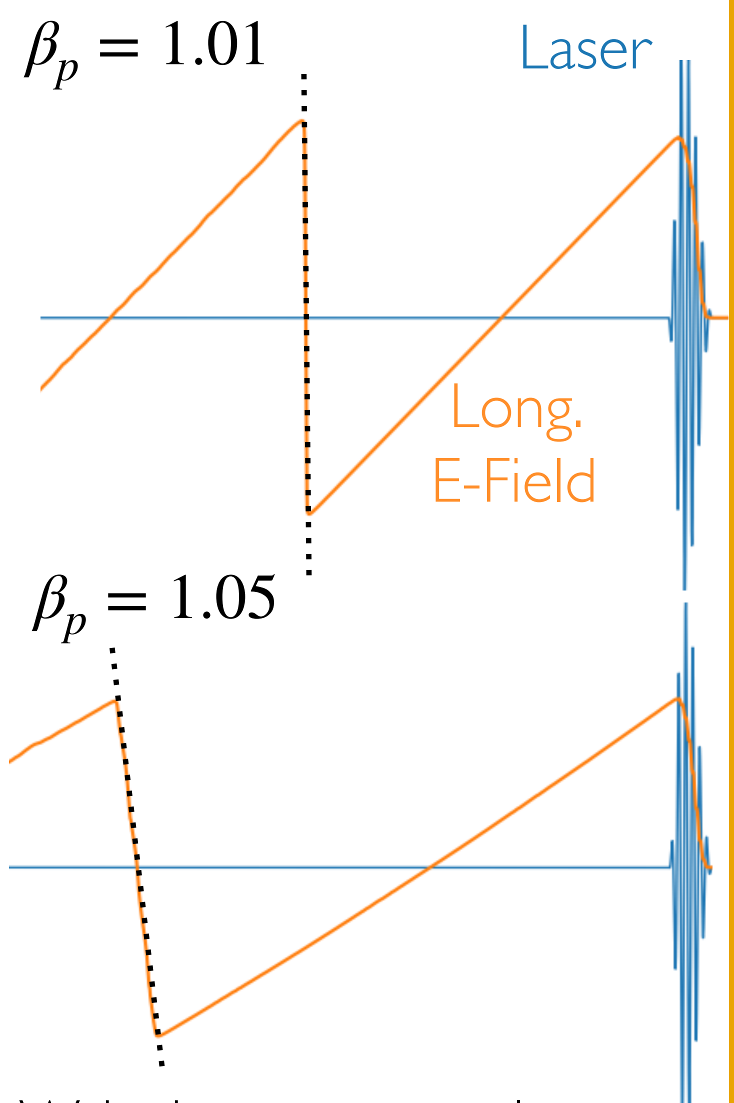


Non-Linear response of the system: there is immoderate electron injection in the subliminal wave (no electrons are injected in the superluminal wave - the amplitude is not affected during interaction)

* J. Palastro, B. Malaca, J.Vieira et al *(submitted)* (**2020**)

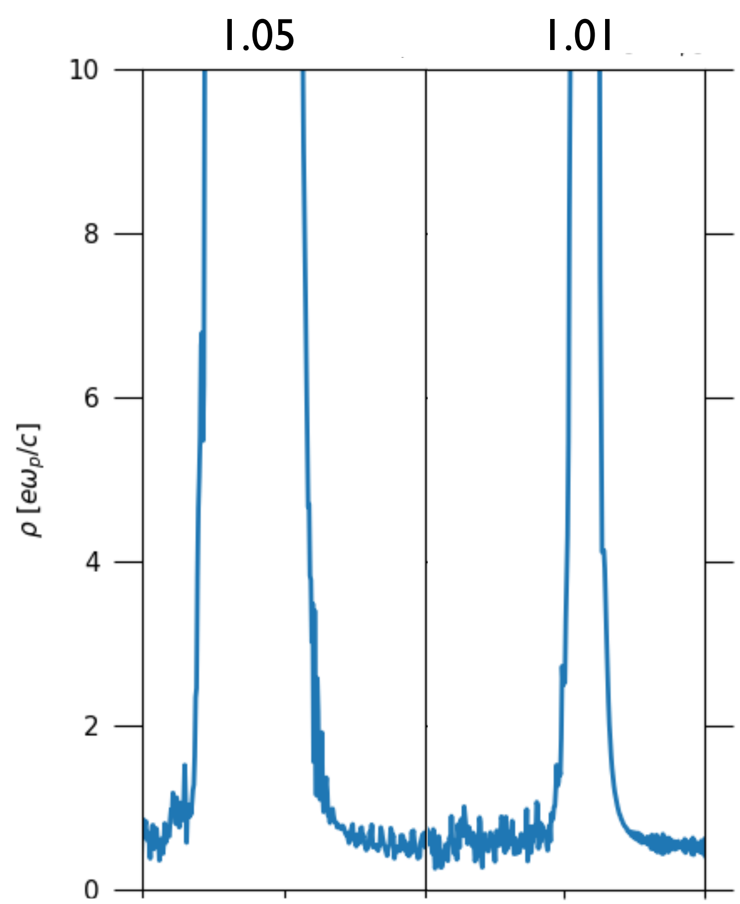
Different superluminal speeds produce different wakes

Plasma wave slope



Wake has a steeper slope as β_p increases

Snapshots $\beta_p = 1.01, 1.05$

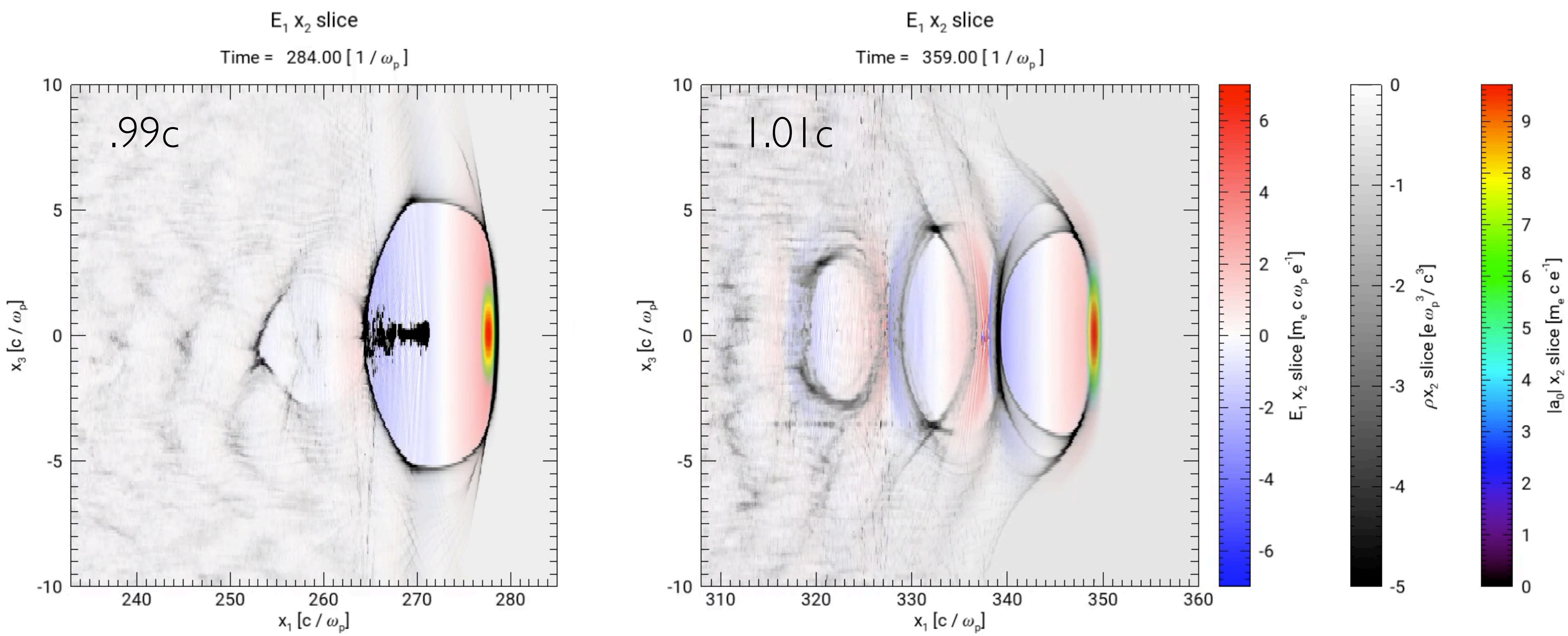


Electron sheath in the back thickens as β_p increases

* J. Palastro, B. Malaca, J.Vieira et al *(submitted)* (**2020**)

How about multidimensional simulations?

3D simulations with a0=15



In the superluminal regime no electrons are injected and therefore the electric field inside the bubble is smoother - possibly a good candidate for staged acceleration.

* B. Malaca et al *(in preparation)* (**2020**)

Conclusions

At low laser intensity

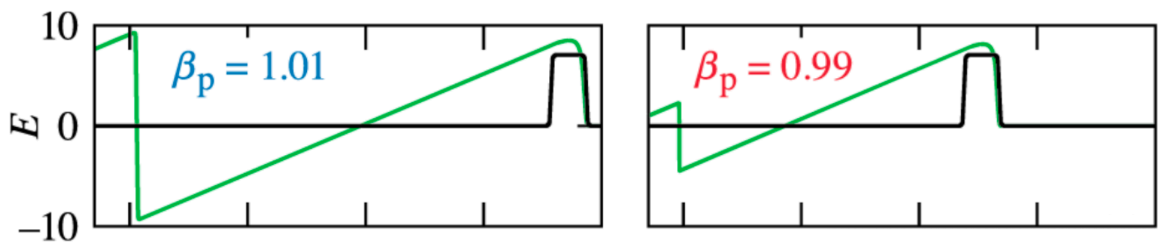
Results are independent from group velocity

Density, electric field and electronic phase space are independent from β

At high laser intensity

Results depend extensively on group velocity

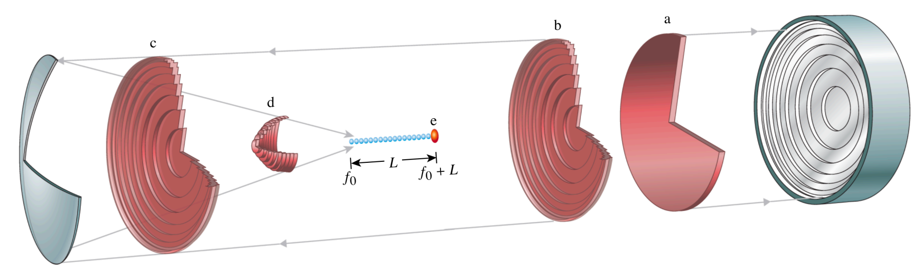
For $\beta = 0.99$ the electric field after the first bucket approaches 0, while it keeps the shape on the superluminal counterpart*

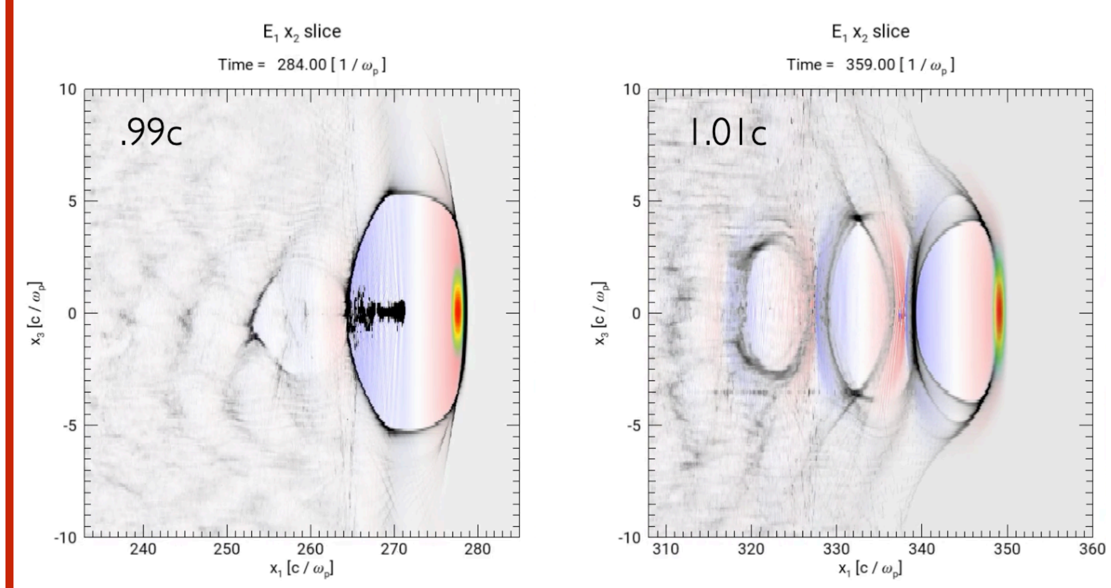


Next steps

3D results are promising

We need to use self-consistent electromagnetic fields to verify the expected plasma response to the purposed experimental setup.





* J. Palastro, B. Malaca, J.Vieira et al *(submitted)* (**2020**)