A plasma-based acceleration method suitable for non-relativistic muons

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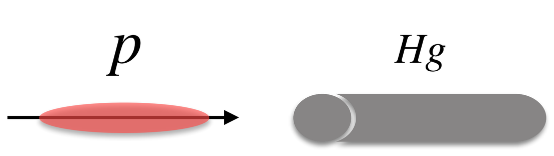
The past years have seen a growing interest in plasma-based accelerator technology since it provides a route to more compact, ecological, yet powerful accelerators. However, even well-established acceleration techniques [1, 2] are only effective with particles traveling close to the speed of light (relativistic particles), leading to the exclusion of heavier particles, e.g., muons from the acceleration process. Nevertheless, plasma-based accelerators could bring substantial advantages by accelerating muons to relativistic energies before they decay [3]. In this work, we show our ongoing effort in trying to fill this gap.

Motivation

- Just as electrons, muons are **fundamental particles**. Their full energy is available in collisions, in contrast to protons (A 14 TeV muon collider with sufficient luminosity would provide a similar discovery reach as 100 TeV proton-proton collider).
- Muons radiate much less than electrons: basically negligible synchrotron radiation ($m_\mu \sim 200\ m_e$).

Nonetheless, the finite life time of the muons ($2.2\ \mu s$) is a **challenge** for conventional accelerator machines, which need to compensate for muon decay losses.

- Plasma-based accelerators [3] could bring substantial advantages by accelerating muons to relativistic energies before they decay.
- A **GEANT4** [4] simulation with a proton beam of $5 \cdot 10^6$ monoenergetic protons ($E_p = 450\ GeV$), hitting a liquid mercury cylinder, was performed (in reality ~10^{12} protons).

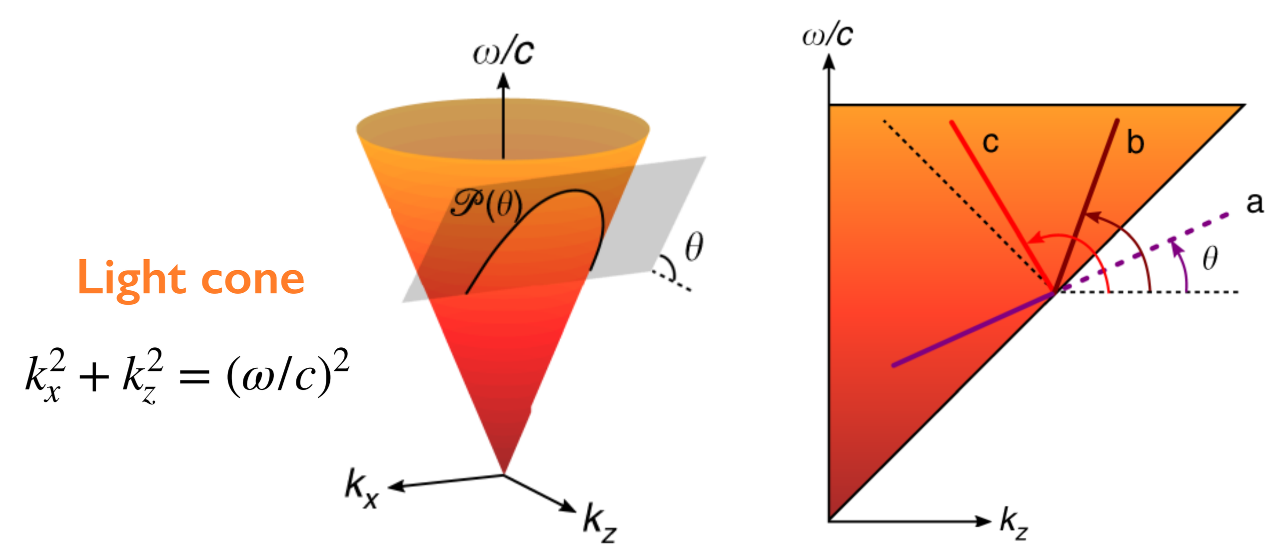


Most of the muons are produced at **lower energies**, while plasma accelerators usually accelerate particles that have already relativistic velocities ($\beta \sim 1$).

Subluminal drivers

The first step toward a plasma-based acceleration method suitable for particles (muons) with non-relativistic velocities is, for example, trying to have **slower drivers** ($v_g < c$).

In free space, we can sculpt optical pulses with a modulation of the spatio-temporal degrees of freedom [4].



$$\omega/c = k_0 + (k_z - k_0)\tan\theta$$

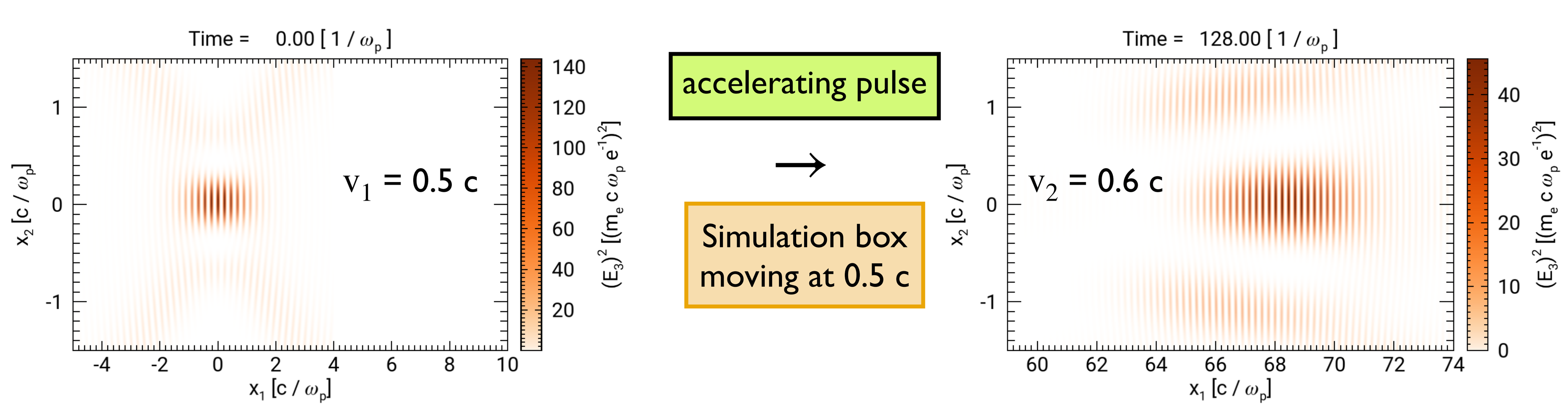
This allows us to have pulses propagating with a group velocity $v_g \neq c$:

$$v_g = \frac{\partial \omega}{\partial k} = c \tan\theta$$

If we assign a **finite spatial spectrum** instead of a singular frequency of the stationary case, we can make these pulses accelerate with an axially encoded changing velocity [6].

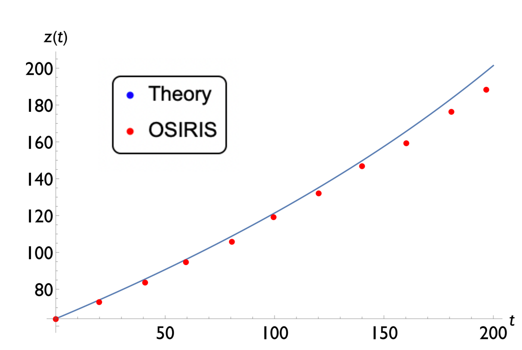
Accelerating spatio-temporal pulses in OSIRIS

Space-time optical pulses able to change group velocity while propagating are now implemented into OSIRIS [7].



$$v(t) = \frac{v_0}{1 - a \cdot t}$$

with a being the spatial acceleration, in this case, here $a > 0$.



Analytical model

We model the energy gain of non-relativistic particles using an external field with a **time dependent phase velocity**.

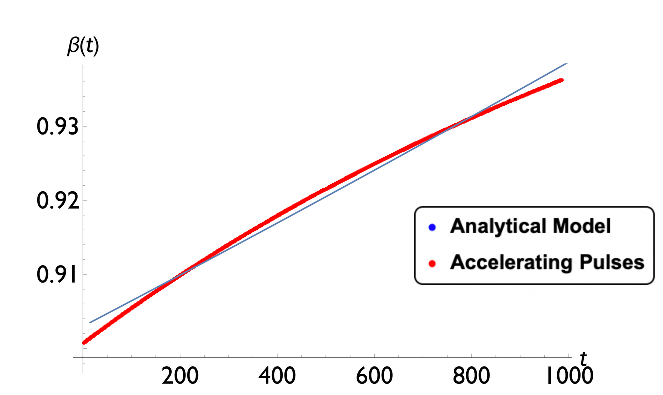
Energy gain:

$$\frac{dp}{dt} = \frac{d}{dt}\left(\frac{\beta_z(t)}{\sqrt{1-\beta_z^2(t)}}\right) = eE_0 cos[k_p(z(t) - \int \beta_\phi(t)\, dt)]$$

Imposing the phase-locking condition ($\beta_z(t) = \beta_\phi(t)$), we find:

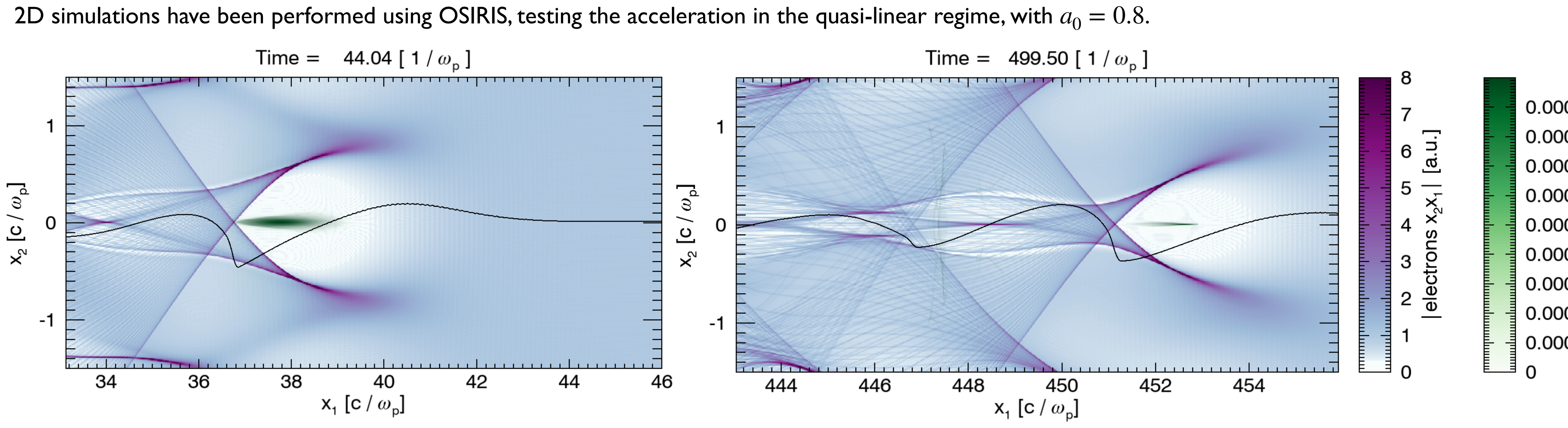
$$\beta_z^2(t) = \frac{\left(\frac{qE_0 t}{mc} + \beta_0\right)^2}{1 + \left(\frac{qE_0 t}{mc} + \beta_0\right)^2}$$

The model allows us to estimate the laser and plasma parameters in the self-consistent scenario to achieve near phase-locking.



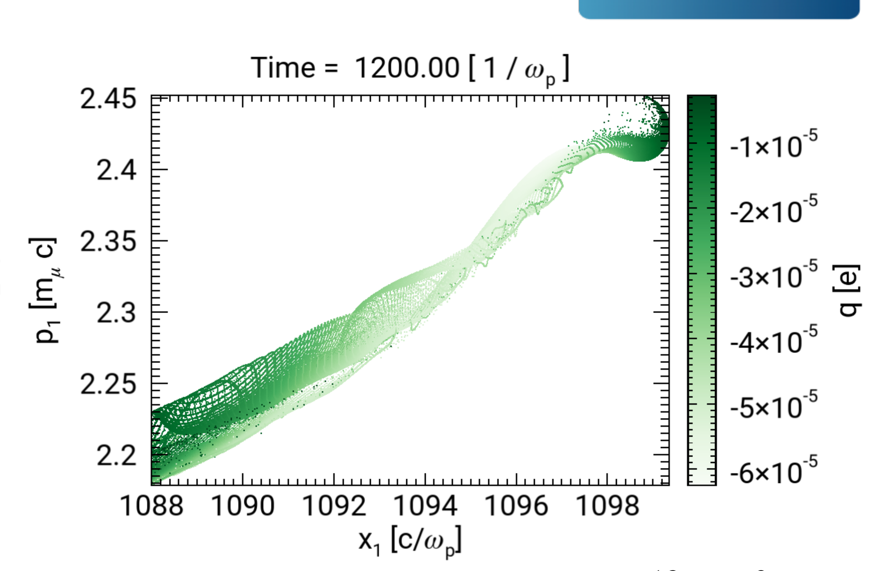
Results

2D simulations have been performed using OSIRIS, testing the acceleration in the quasi-linear regime, with $a_0 = 0.8$.



Simulation box moving at 0.9 c

Figure 1: 2D OSIRIS simulation during the acceleration process. The plasma electron density is represented in scale of blue to purple and the muons density in scale of greens. The black line represents a lineout of the longitudinal electric field.



With a plasma density of $n_0 = 10^{18}\mathrm{cm}^{-3}$:

energy gain of 50 MeV in 5 mm (acceleration gradient of ~10 GeV/m)

Figure 4: Phase space from the 2D OSIRIS simulation after t = 1200 [1/ω_p]. Space, energy, and momentum are in normalized units.

Conclusions and Future Work

- Plasma accelerators so far are only applicable to relativistic particles.
- To fill this gap, we propose the possibility of accelerating non-relativistic particles using optical wave packets with a group velocity smaller than the speed of light.
- Accelerating space time wave packets have been implemented into OSIRIS, and then tested as drivers for the acceleration of non-relativistic muons.
- In the future, we will investigate the **non-linear** regime to see if we can improve the energy gain.

References

[1] T. Tajjima and J. M. Dawson, Physical Review Letters **43**, 267 (1979)
[2] C. Joshi, Physics Today 56 (6), 47 (1993).
[3] K.R. Long, et al Nature Physics volume 17, 289–292 (2021).
[4] H. Kondakci,, Y. F. Abouraddy, Nature Communications, 10, 929 (2019)
[5] S. Bulanov et al, Phys. Rev. E **58**, R5257(R) (1998).
[6] M. Yessenov and Y.F. Abouraddy, Phys. Rev. Lett. 125, 244901 (2020).
[7] R.A. Fonseca et al., Phys. Plasmas Control. Fusion 55, 124011 (2013).

ACKNOWLEDGEMENT - This poster presentation has received support from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730.