A plasma-based acceleration method for heavier particles

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Motivation

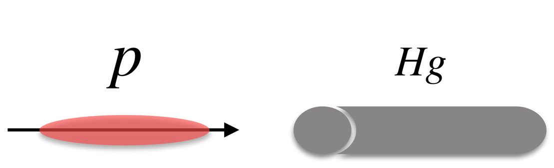
Conventional accelerating techniques are not fast enough to accelerate short-lived particles efficiently, what are we excluding?

Muons (μ): difficult to accelerate with conventional techniques ($\tau_\mu = 2.2\ \mu s$) even if there is a huge interest in the high-energy physics community in building a muon collider [1].

Pions (π): impossible to accelerate with conventional accelerating machine (τ_π = 18 ns). So far, only studied from secondary decay. If first accelerated, they become a better source of muons.

What about a plasma based accelerator (PBA) [2,3]?
In this work the acceleration of muons using a PBA will be tested.

➠ 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).

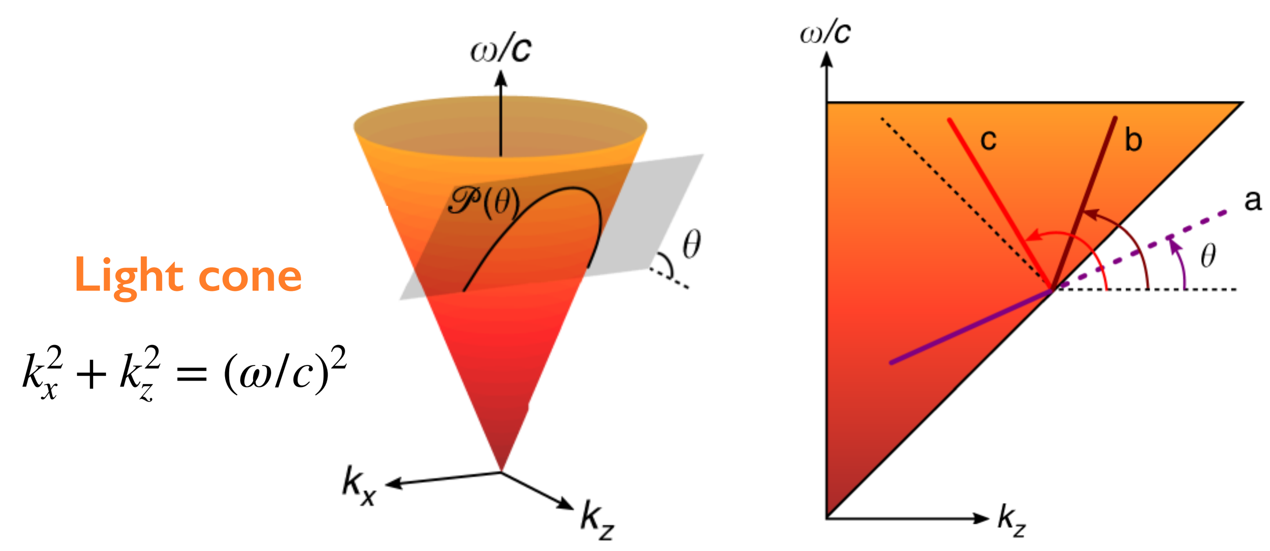


Most of the muons are produced at **lower energies**, while plasma accelerators usually accelerate particles that have already relativistic velocities ($\beta \sim 1$).

Slower Wakes Using 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 [5].



Hyperplane

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

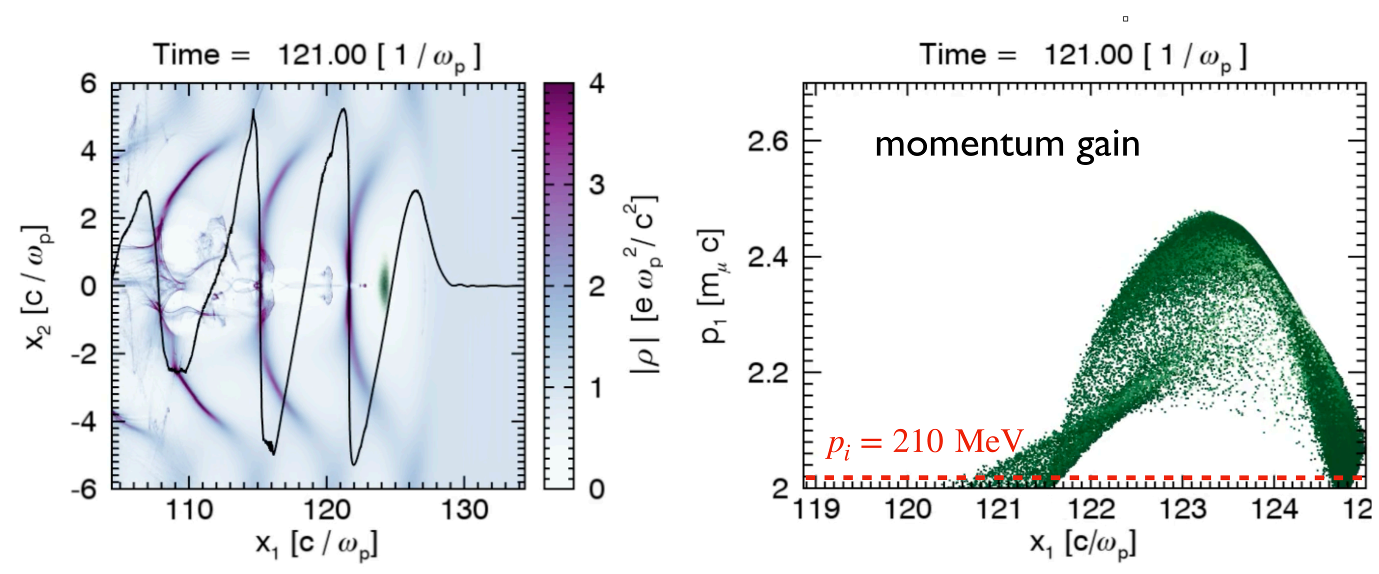
This allows us to have pulses propagating with a group velocity $v_g \neq c$:

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

The subluminal pulses gave the best performances if **tightly focused**, leading to more symmetrical and stable acceleration wakes.

Having a Subluminal Driver is not Enough: Dephasing

Is a subluminal driver enough to accelerate the muons to relativistic energies?
→ Let us consider a case with $v_d = 0.9c$ and $v_\mu^0 = 0.9c$



Quickly, the muons become faster than the wake, overtaking it and losing the good position to be accelerated (only up to 0.92c)!

Having a subluminal driver is not enough.

Varying the Plasma Density Allows Wake Speed Control

If we have a driver, moving at velocity v_d, through a region of varying plasma density, the longitudinal position of electron spike at the back of the accelerating wake will be [6]:

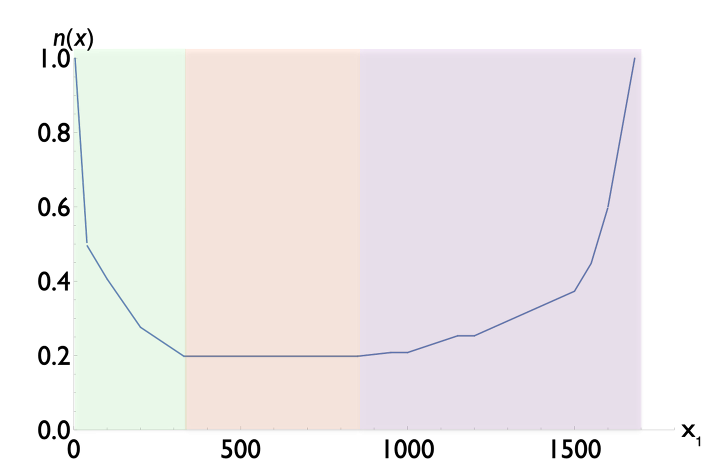
$$x(t) = v_d t - \lambda_p(x(t))$$

With a velocity: $v(t) = \frac{dx(t)}{dt} \simeq v_d\left(1 - \frac{d\lambda_p(x)}{dx}\right)$

Since $\lambda_p = 2\pi\frac{c}{\omega_p}$ and $n = \omega_p^2$ (in normalized units) $\rightarrow$ $n(x) = n_0\frac{\lambda_{p0}^2}{[(1 - v_w/v_d)x + \lambda_{p0}]}$

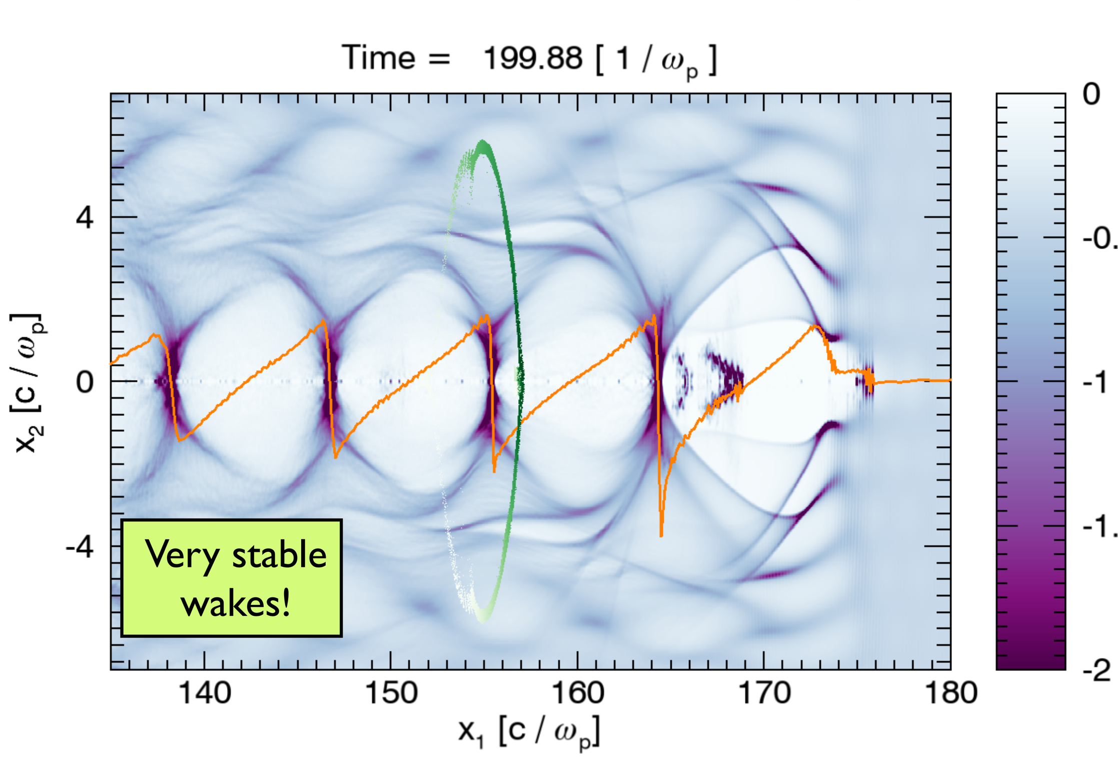
Similarly, for n[th] secondary wake: $v_w^n = n(v_w - c) - c$

Our costumized density profile will be structured as:
➠ An initial density **down ramp** region, to slow down the wake and trap the muons.
➠ A **constant** density region, after the muons reach v_d.
➠ A density **up ramp** region to mitigate dephasing.



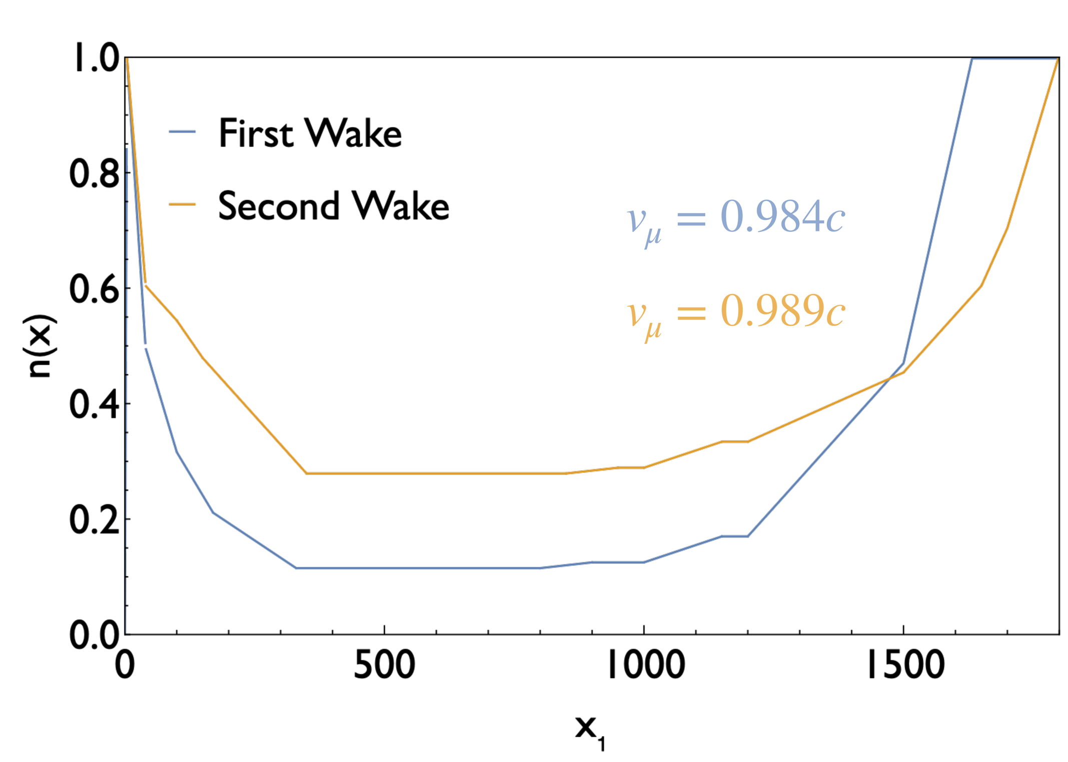
Simulations Results: We Brought Muons To Relativistic Velocities

Quasi-3D simulations of the acceleration method proposed have been performed using OSIRIS [7] for the acceleration of a muon beam with initial velocity of $v_\mu = 0.9c$.



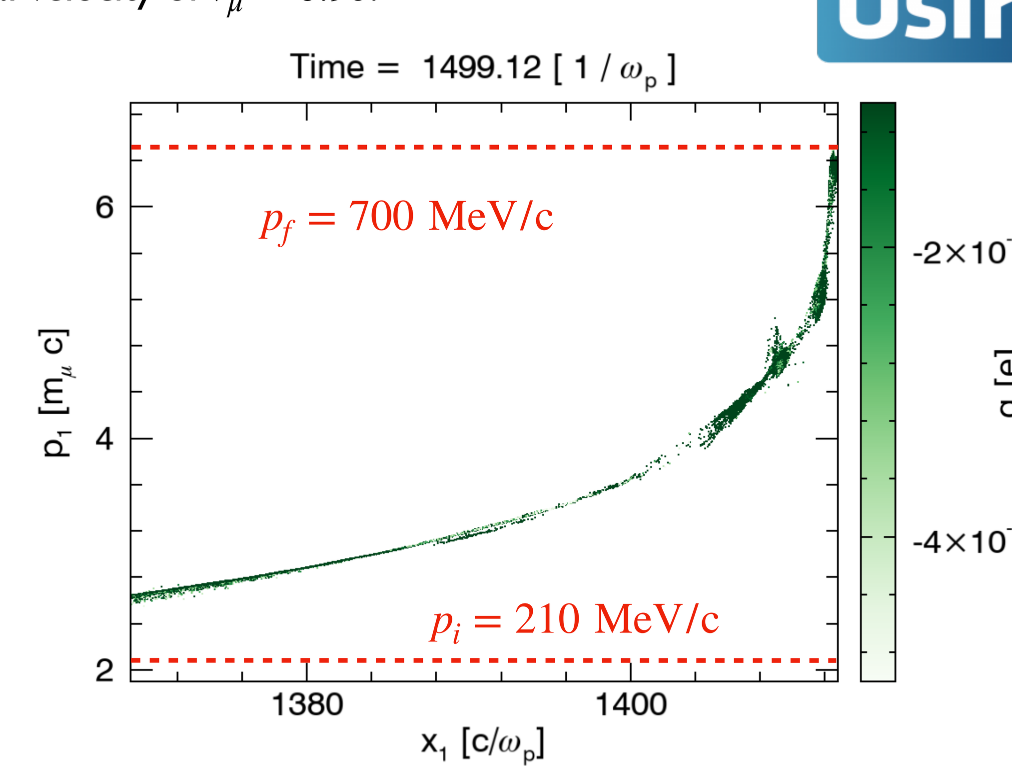
Using a driver with $v_d = 0.96c, a_0 = 10$ and $\omega_0 = 20$

Figure 1: Acceleration process plot from the simulation. The plasma density is in scale of blue to purple and the muons density in scale of greens. The longitudinal electric field line out is in orange.



✓ Accelerating using the second wake gave the best results.

Figure 2: Costumized density profile comparison. The second acceleration wake is slightly slower than the first one, so the initial down ramp phase can be less steep.



✓ We brought the muons to relativistic velocities

Figure 3: Momentum gain in the quasi-3D OSIRIS simulation after t ≃ 1500[1/ω_p]. Space, energy, and momentum are in normalized units.

Conclusions and Future Work

➠ Short-lived particles can not be accelerated with conventional accelerating techniques efficiently.
➠ 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 in combination with a costumized density profile.
➠ The acceleration proposed succeeded in bringing the muons to relativistic velocities in one acceleration stage.
➠ In the future, the same technique will be applied to the acceleration of pions, that are impossible to accelerate with conventional accelerating techniques.

References

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