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Laser wakefield acceleration of electrons by a circularly polarized laser pulse

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Research Activities

- Laser-plasma based particle acceleration
- Laser wakefield acceleration
- Proton acceleration
- Laser-plasma based electromagnetic radiation
- Parametric instabilities

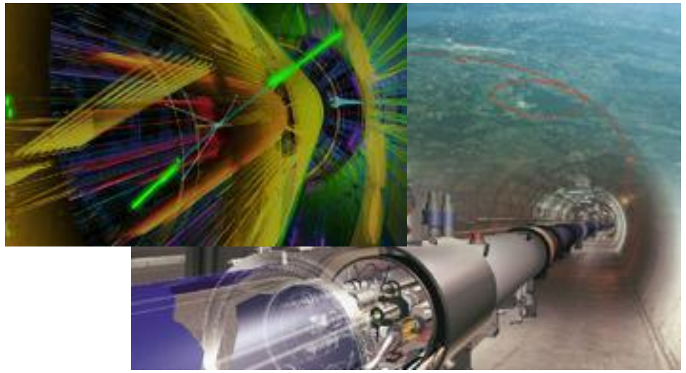
Outline

- Laser wakefield accelerators
- Electron injection mechanism
- Laser polarization effects
- Recent results
- Conclusion

Motivation

- Major goal is to improve the beam quality in laser wakefield acceleration (LWFA).
- Density dependence of beam parameters in LWFA creates a scope to study electron acceleration in density modulated plasma.
- Study of laser polarization is quite significant as it affects the plasma dynamics.
- Using particle-in-cell simulations, we demonstrate the influence of laser polarization on the quality of electron bunches.

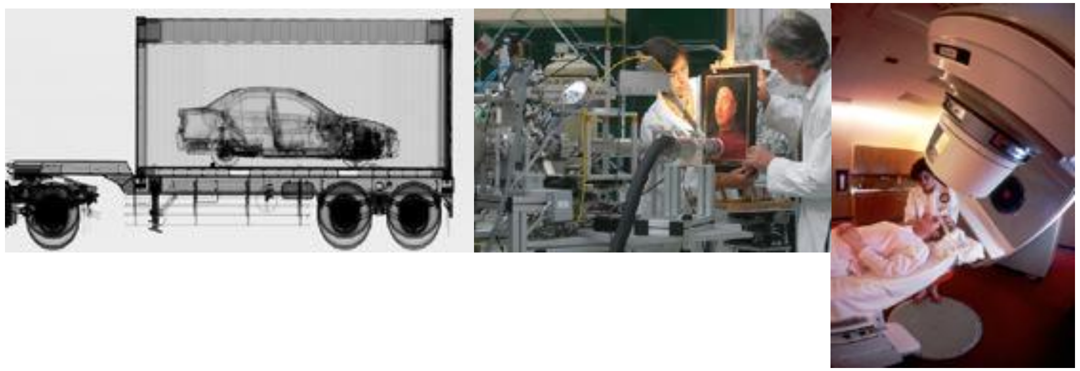
Particle accelerators are drivers of science and technology



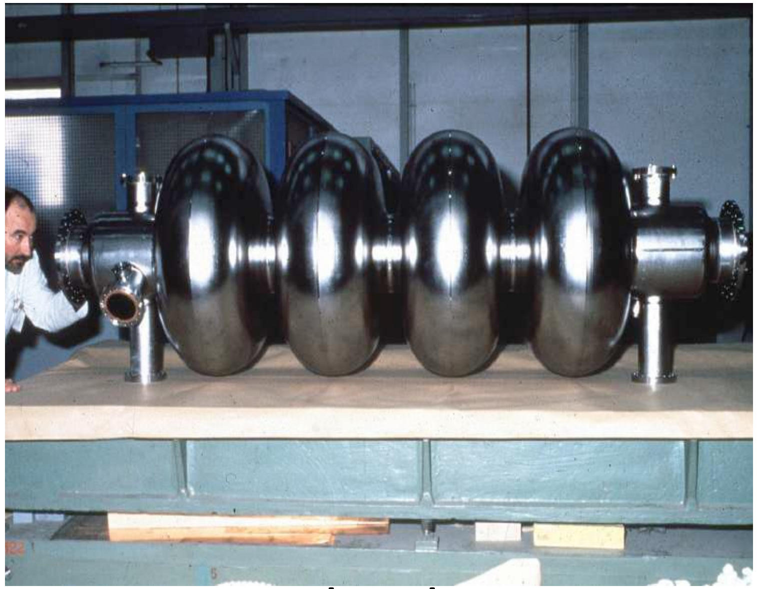
- High energy colliders are at the forefront of fundamental physics discovery

- Light sources enabled by particle accelerators are revolutionizing biotechnology, material science and condensed matter physics research

- Particle accelerators are used throughout industry, homeland security and medicine, from materials engineering to cargo scanning to cancer treatment



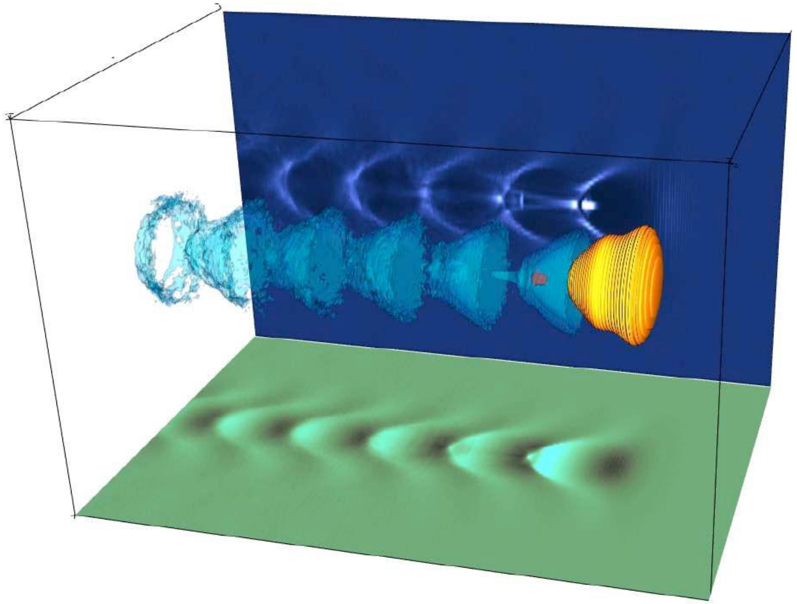
Compactness of laser plasma accelerators



RF Technology

1 m => 50 MeV Gain
Electric field < 100 MV/m

Cost ↓ Size ↓



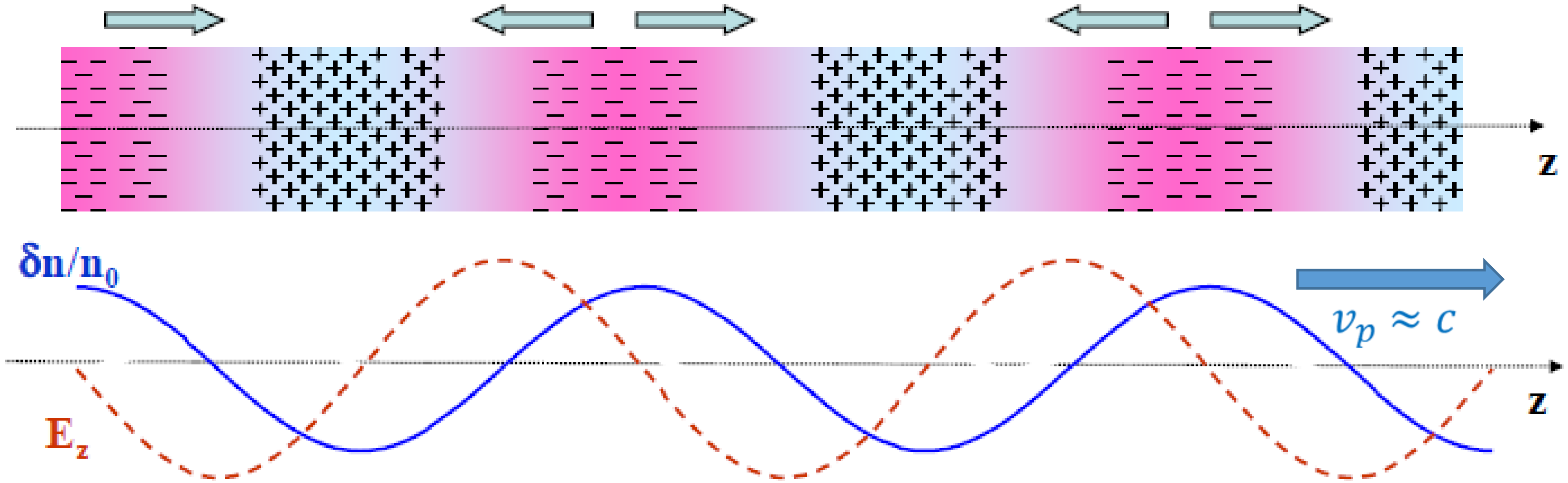
Plasma Accelerators

1 mm => 100 MeV Gain
Electric field < 100 GV/m

V. Malka *et al.*, Science **298**, 1596 (2002)

Plasma as an accelerating medium

- Plasma is already ionized : Collection of free electrons and ions

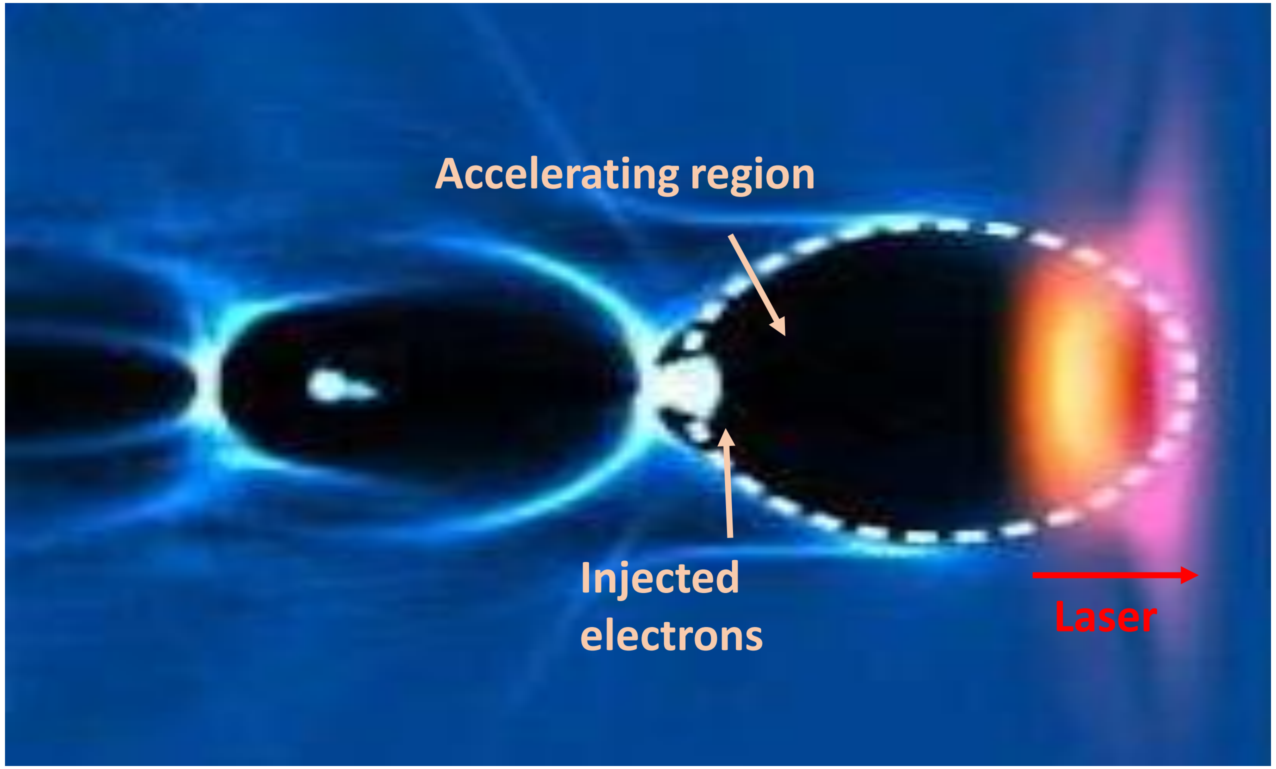


$E_z \approx 300\ \mathrm{GV/m}$ (for $n_0 = 10^{19}\ cm^{-3}$)

Plasma wave created behind the laser pulse → Laser wakefield

Laser Wakefield Accelerator : LWFA

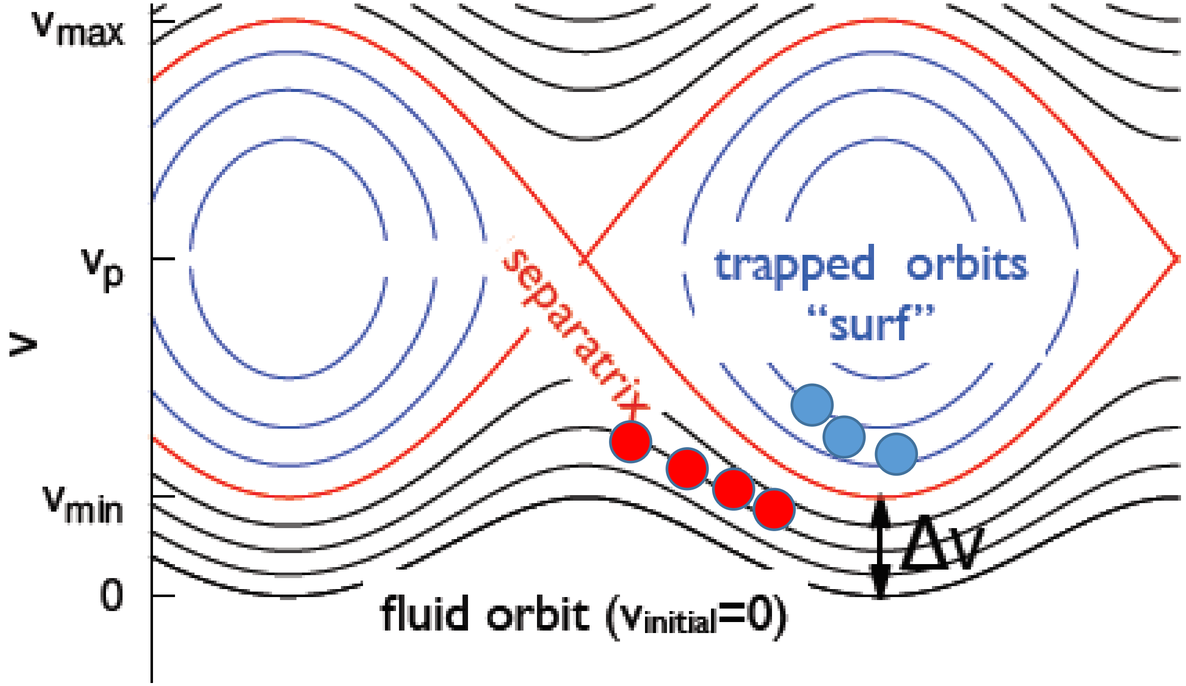
- ❑An intense laser pulse pushes electrons away from axis.
- ❑Electron void is formed behind the laser.
- ❑Ions inside the bubble apply a space charge force and pull the electron towards the laser axis.



Lu, W. et al. *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007)

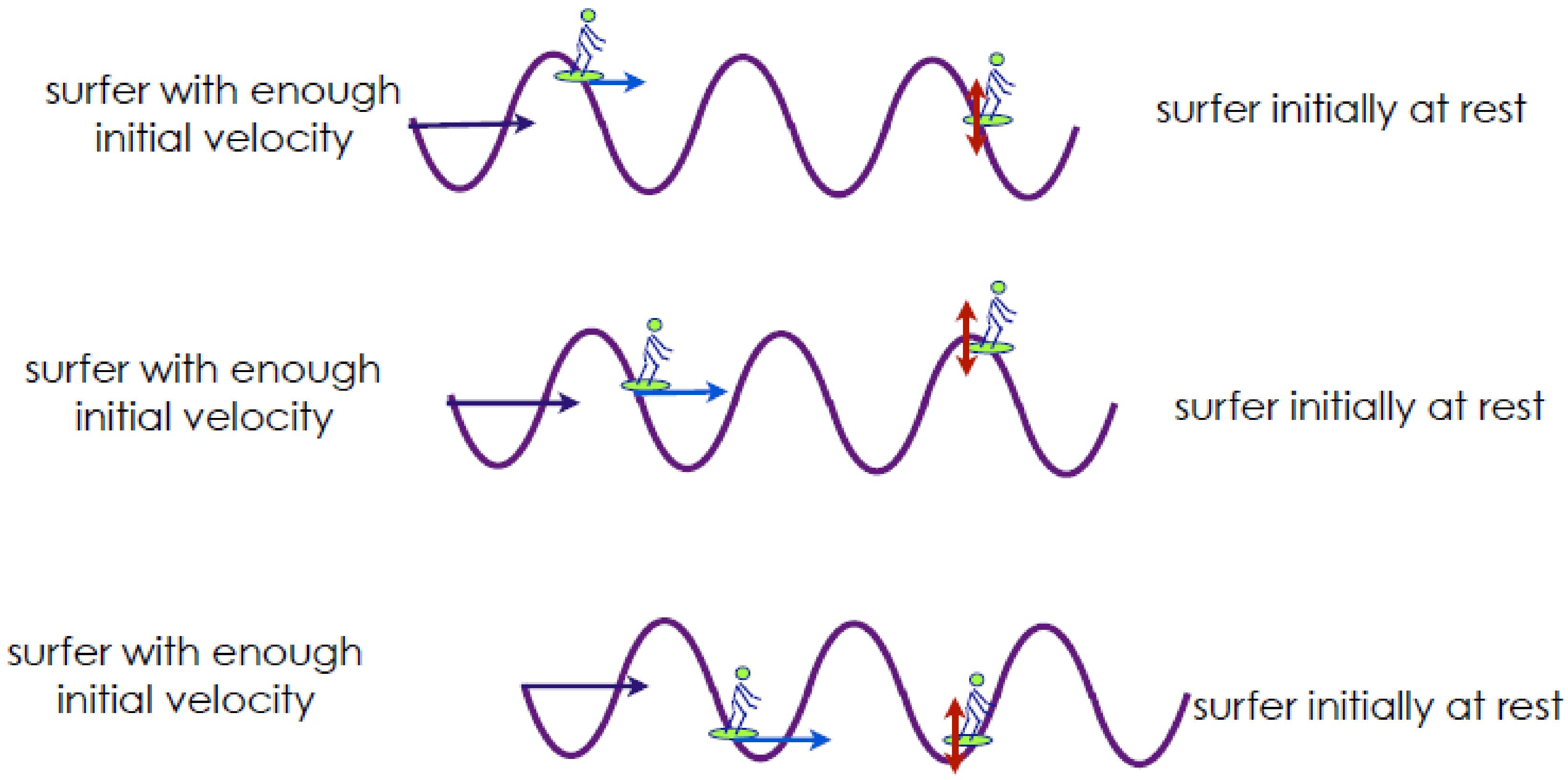
Injection criteria

- ❑ Trapped orbits allow high energy gain
- ❑ One needs to transfer enough velocity Δv
- ❑ Untrapped electrons
- ❑ Trapped electrons



Phase Space Representation

Trapping energy : analogy electron/surfer

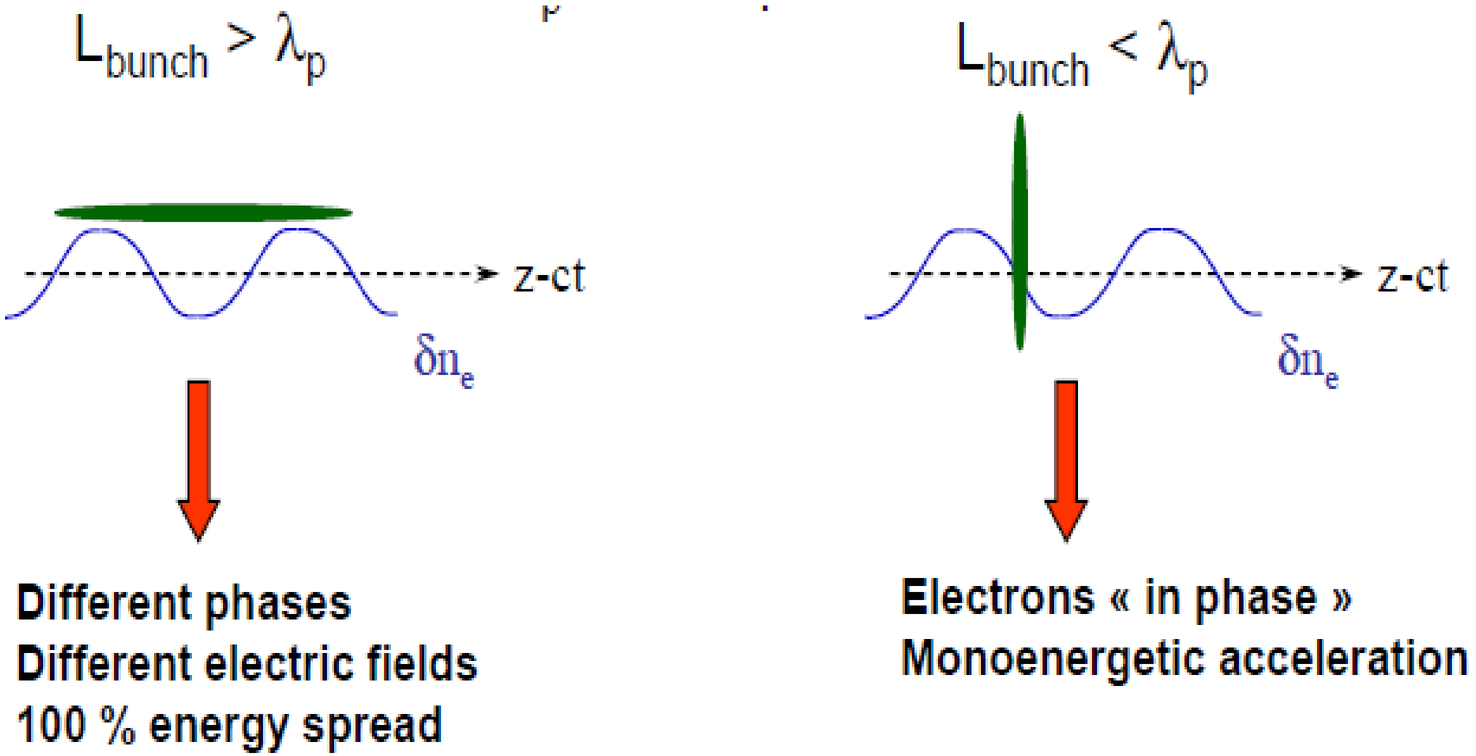


Why injection is so important?

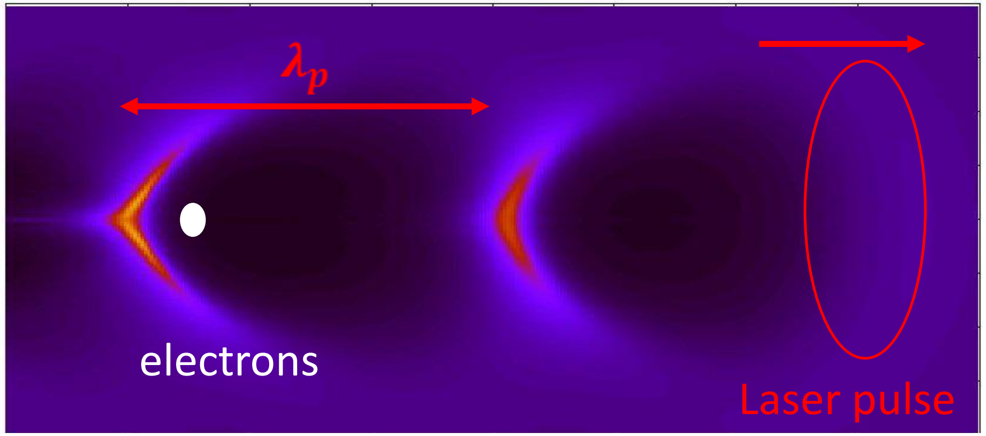
- Better stability
- More control
- Possibility to tune the beam parameters independently
- Getting away from self-injection

Good injection scheme

- small energy spread
- short electron bunch
- Small emittance
- Control over beam parameters



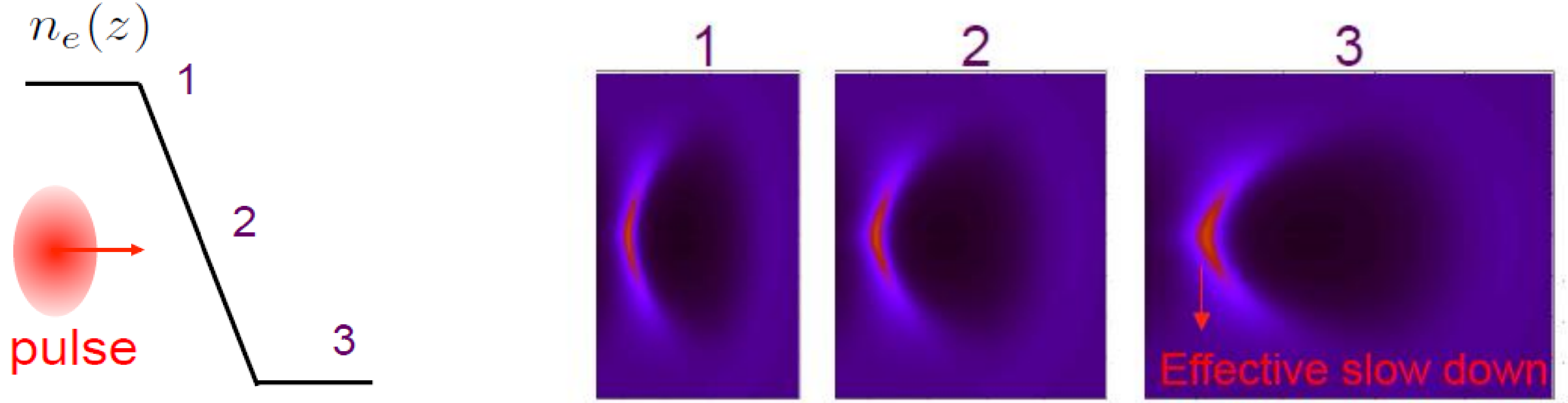
How do we inject electron into the wakefields?



Three fundamental methods for injecting electrons in the wake

- ❑ Give a initial kick to electron (paddling surfer) → colliding pulse injection
- ❑ Drop electrons in the wake at the right phase → ionization injection
- ❑ Slow down the wakefield → injection in density gradient

Principle of density gradient injection



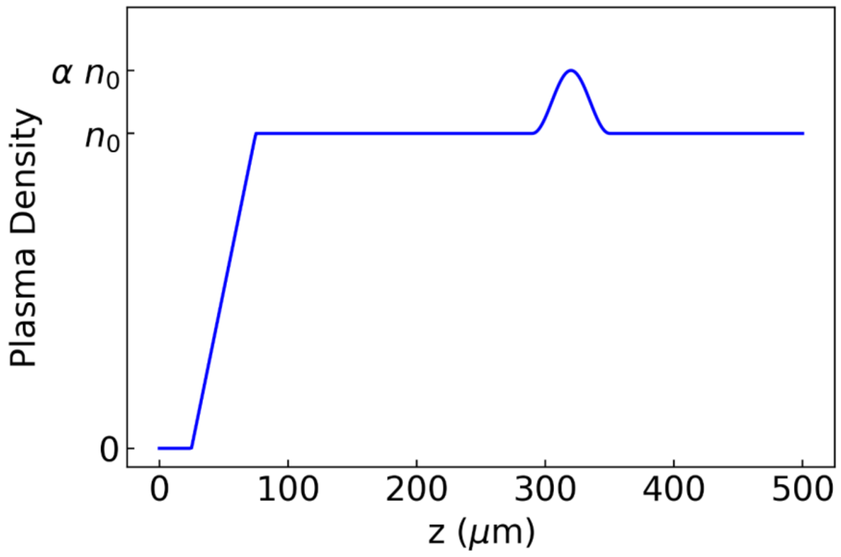
H. Suk, N. Barov, and J. B. Rosenzweig, E. Esarey, Physical Review Letters **86**, 1011 (2001)

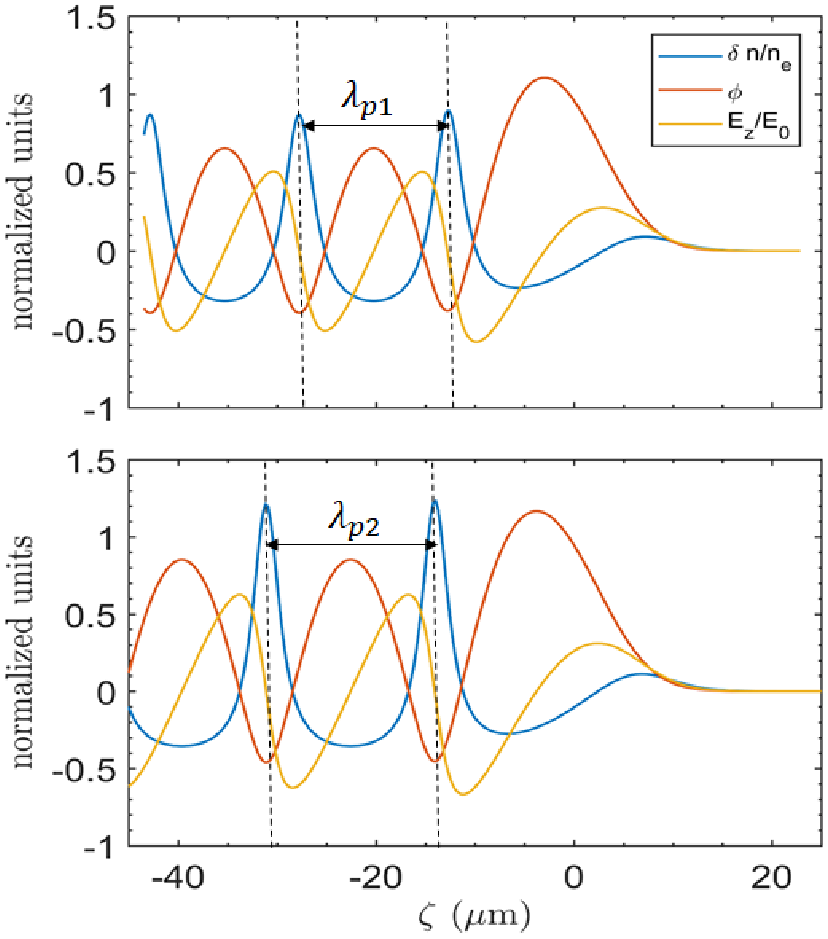
In the density gradient, λ_p increases

- ❑ causes the plasma wave to elongate
- ❑ effective slow down of the back of the plasma wave
- ❑ effective decrease of the phase velocity

$\rightarrow$ Facilitates trapping

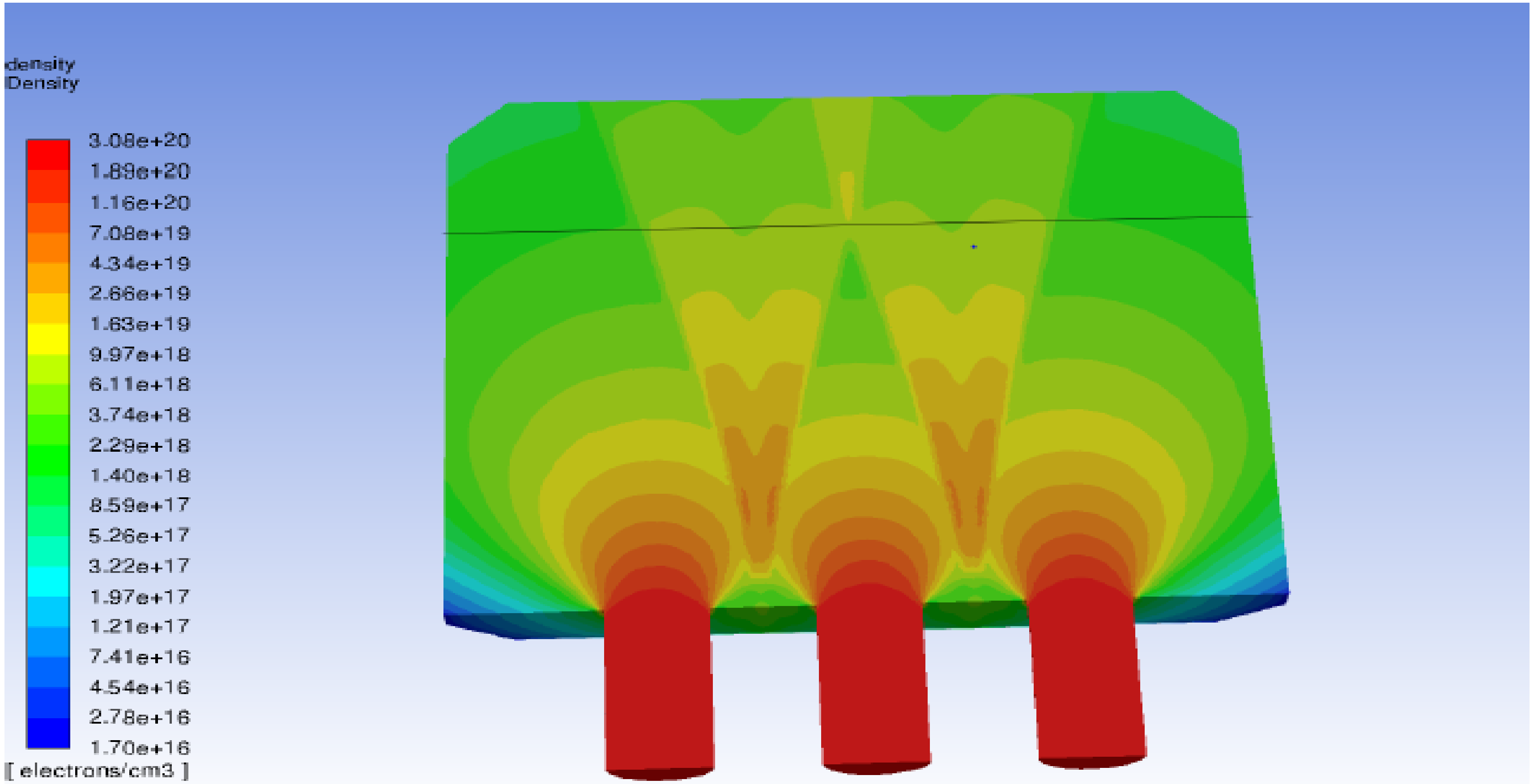
Injection using density bump





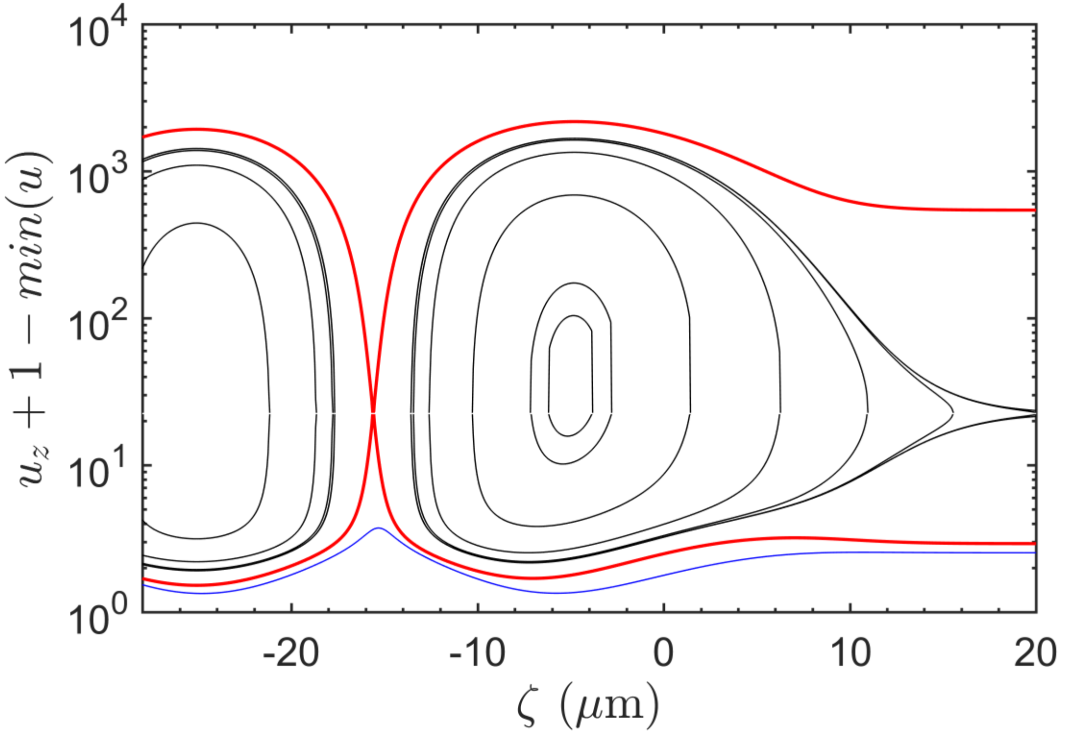
The oscillation period is longer in the low density region The electrons are dephased with respect to the background plasma-wave electrons and become trapped.

Creating density bump using multiple gas jet

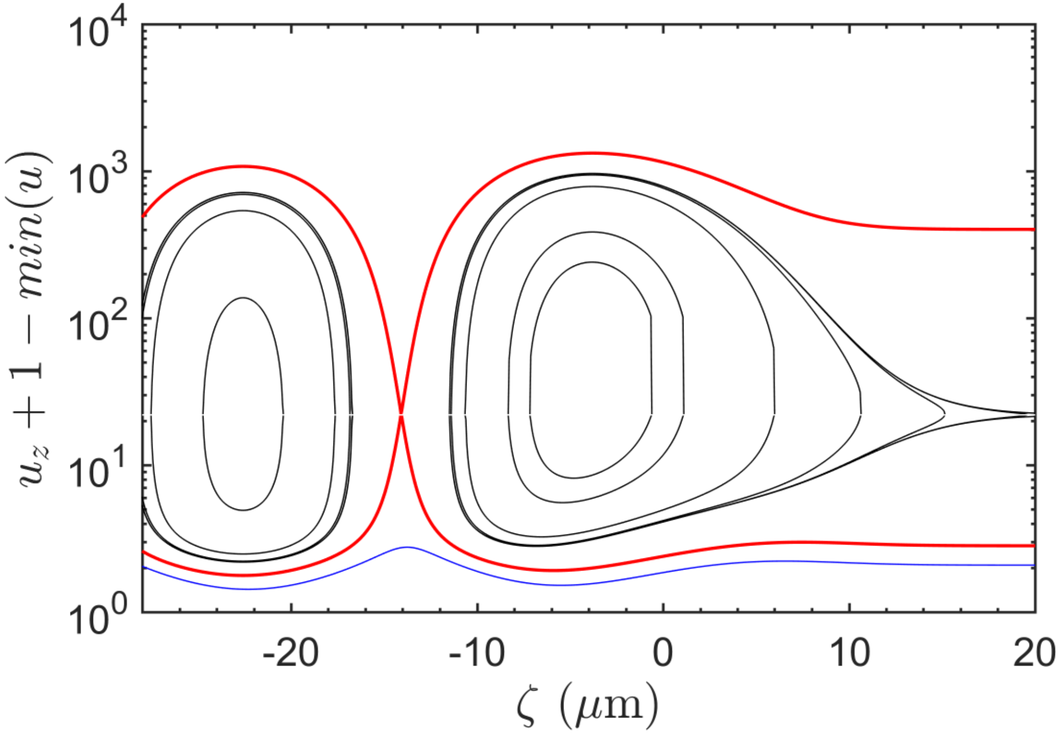


Tooley *et al.* [Phys. Rev. Lett. **119**, 044801 (2017)]

Phase space trajectories (Laser polarization)



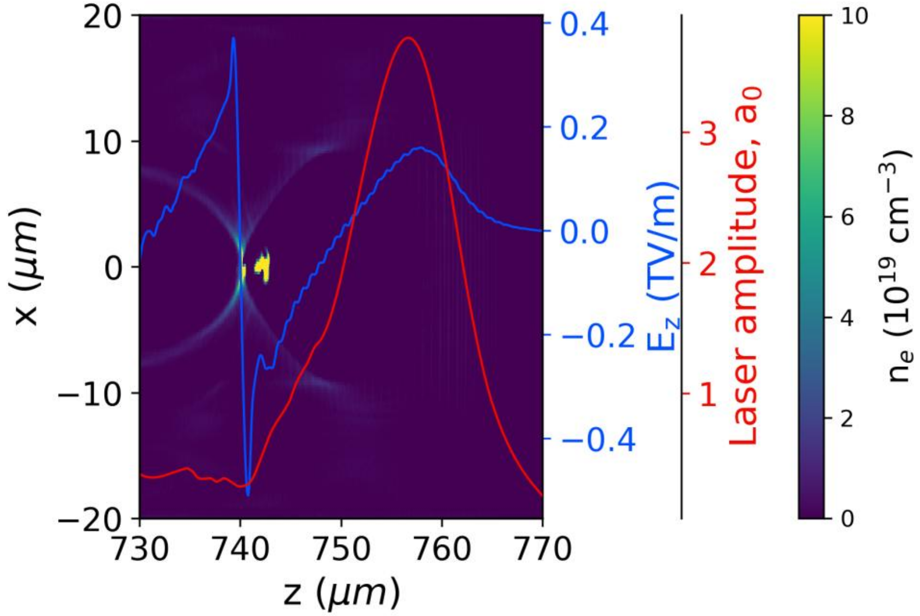
Linearly Polarized (LP)



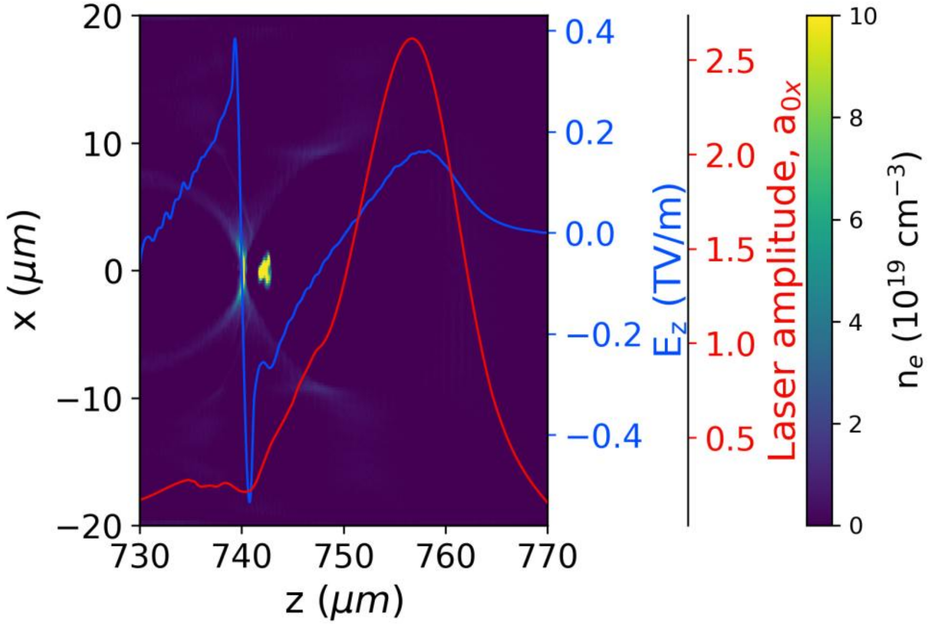
Circularly Polarized (CP)

Simulation results

Linearly Polarized (LP)
Trapped charge = 95 pC

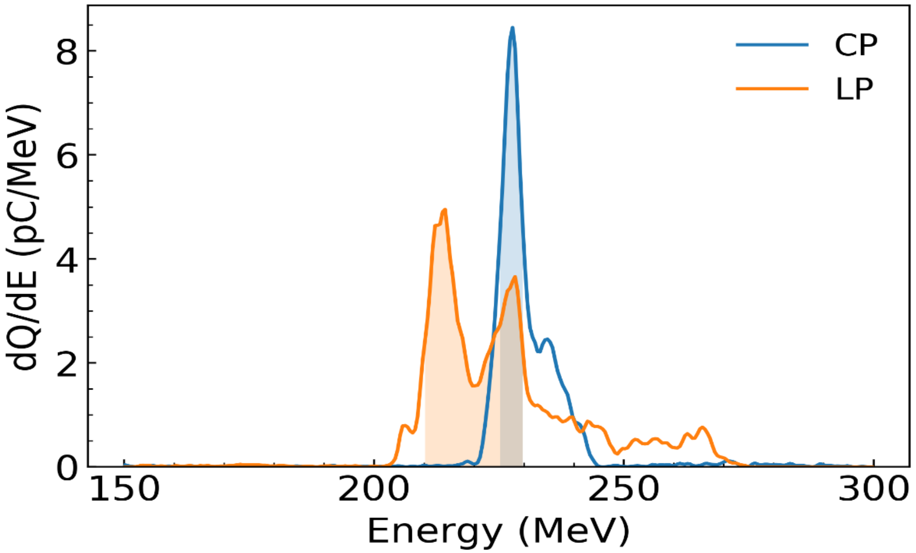


Circularly Polarized (CP)
Trapped charge = 68 pC



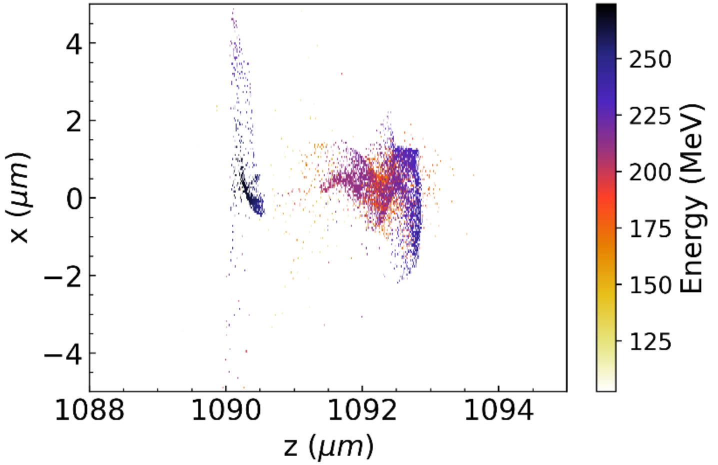
- The wakefield seems overloaded (enhanced beam loading) in LP case.
- Circular polarization leads to significant differences in self-injection because it modifies the initial conditions for the electron trajectories and trapping is extremely sensitive to the details of the trajectory.

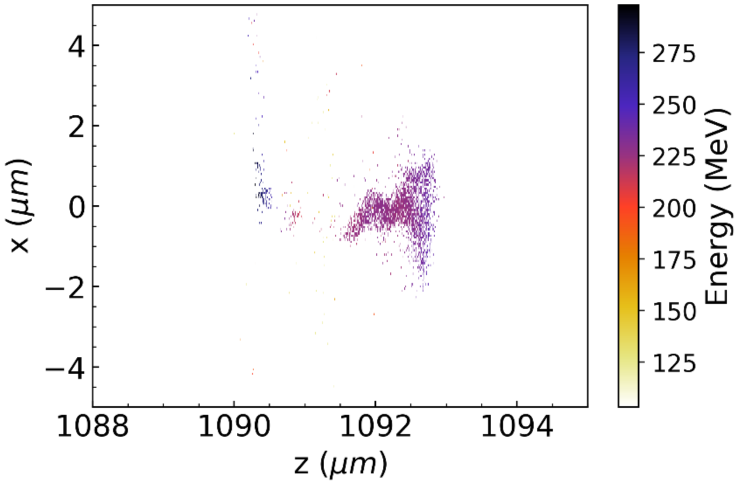
Better quality electron beam obtained from CP



	LP	CP
Relative energy spread (%)	9.3 %	2.6 %
Emittance ($\epsilon_x - \epsilon_y$) (π mm $mrad$)	$2 - 0.57$	$0.64 - 0.57$

•The CP laser reduces the transverse momentum of the electrons due to symmetric polarization ($\frac{a_0}{\sqrt{2}}$).





Conclusion

- Tune electron bunch charge with density bump
- Localized injection corresponds to the location of the bump
- Controlled injection into the plasma wave accelerator
- Small energy spread and improved emittance in the direction of laser polarization.
- Improved beam quality from circularly polarized laser pulse will open the way to accelerator development.

Thank You Very Much!