Super-ponderomotive electrons in laser-irradiated plasmas

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in collaboration with

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Outline

- Introduction and motivation
- Electron acceleration in a plasma by a long laser beam
- Analytical single electron model for electron acceleration in a plasma channel
- Temporal resolution criterion for PIC simulations
- Summary

Introduction

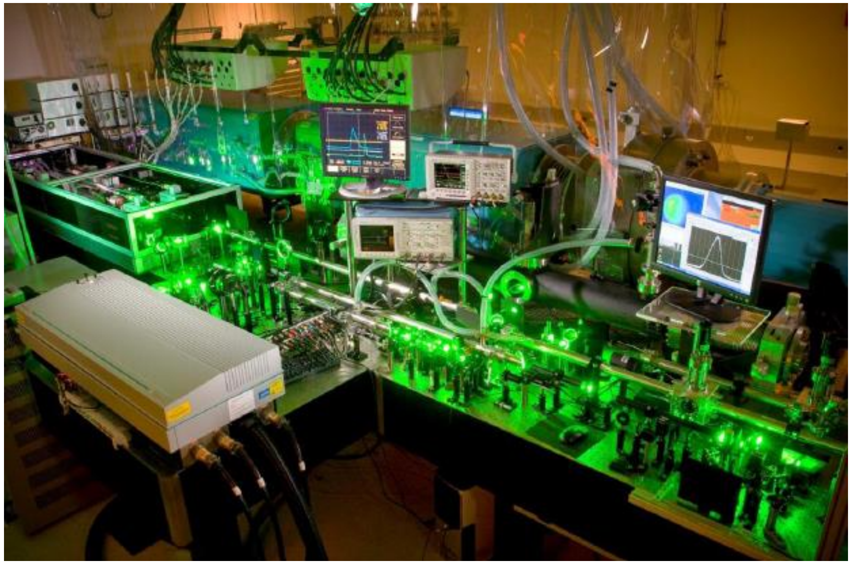
- Laser-plasma acceleration – key technology for a new generation of compact particle and radiation sources.

- Table-top PW-class, short-pulse lasers (kJ on a ps scale) are becoming available at universities.

- Lasers produce plasmas under extreme conditions, transferring laser energy to plasma electrons.

- Electrons deposit their energy into various channels leading to production of energetic protons, X-rays, positrons, or neutrons.

Texas PW in operation



Why laser-plasma accelerators?

The Large Hadron Collider

- Conventional particle accelerators are large and expensive due to the breakdown limit of 20 MV/m.
- Laser systems generate significantly higher fields (large amounts of electromagnetic energy in a small volume over a short period of time).
- A single electron irradiate by a plane electromagnetic wave retains no kinetic energy.
- Techniques other than the vacuum-based acceleration are needed.

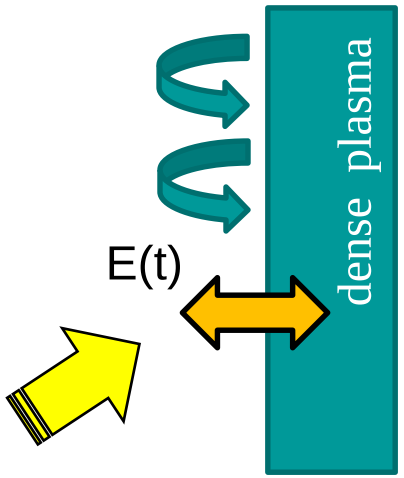
Heating in an overdense plasma

- Laser irradiating an overdense plasma ($\omega << \omega_p$) interacts only at the surface.

- The normal component of E extracts electrons, accelerates them, and re-injects them into the plasma.

- The role of the plasma:
  - to provide electrons;
  - to facilitate the energy retention;

- A two component electron population with a hot minority can be generated, provided that the injected electrons are collisionless.



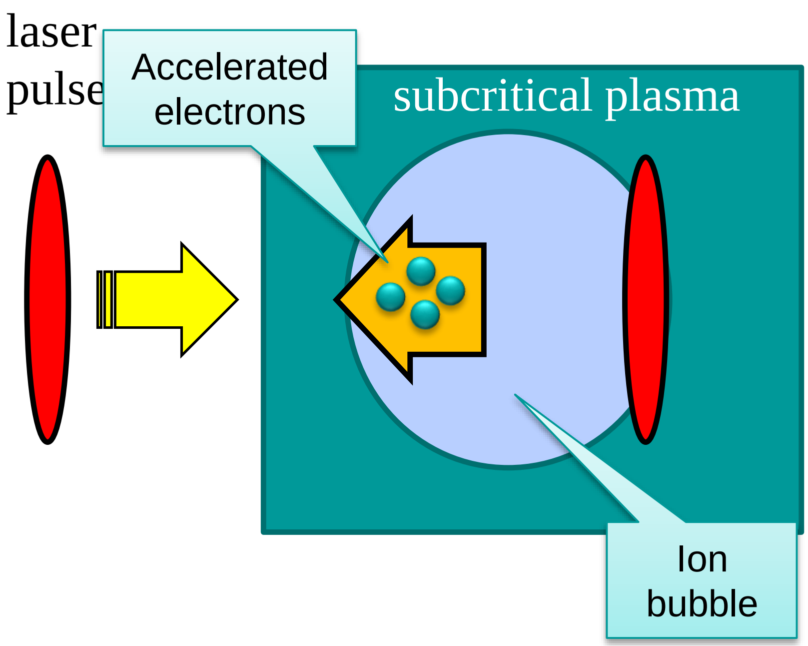
Non-relativistic and relativistic regimes

- The electron momentum gain is $\frac{\Delta p}{\Delta t} \approx |e| E_0 \rightarrow \frac{p}{mc} \approx a_0 \equiv \frac{|e| E_0}{m\omega c}$
- Normalized amplitude a_0 determines the transition from non-relativistic to relativistic regime.
- In the non-relativistic case (a_0 << 1): $\varepsilon \approx \frac{p^2}{2m} \approx \frac{1}{2} a_0^2 mc^2 \propto I$
- The energy can be further increased via stochastic heating.
- In the relativistic case (a_0 >> 1): $\varepsilon \approx pc \approx a_0 mc^2 \propto \sqrt{I}$
- Many applications require copious electrons with energies in the 10's of MeV range.

I = 10^{20} W/cm^2
λ= 1 μm
a_0 = 8.5
ε = 4 MeV

Acceleration in a subcritical plasma

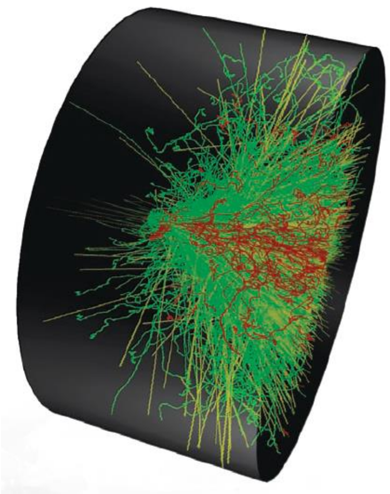
- Key advantage of subcritical plasma: extended interaction length.
- Wakefield acceleration: axial field of the plasma accelerates electrons.
- Wakefield acceleration produces GeV mono-energetic electron bunches.



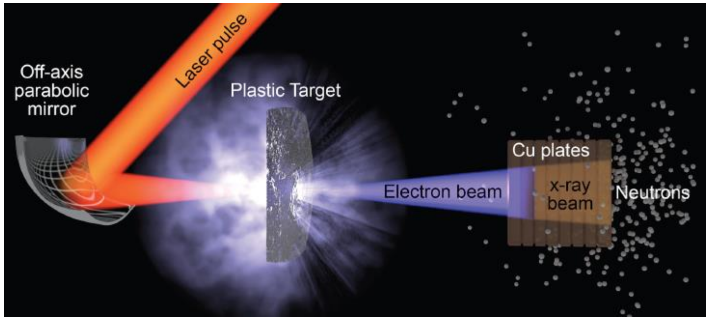
- The bubble size is c/ω_p, so the pulse must be shorter ($\tau \ll 1/\omega_p$).
- The bubble size limits the number of accelerated electrons ($N_e \ll N_i$).
- A non-wakefield mechanism is needed to produce copious energetic electrons.

Non-wakefield regime

- **<u>Regime of interest:</u>** long high-intensity laser pulse ($\tau \gg 1/\omega_p$ and $a_0 \gg 1$) irradiating an extended subcritical plasma ($\omega_p \ll \omega$ and $l \gg \lambda$).
- What is the heating mechanism in this case?
- Laser prepulse creates an extended subcritical preplasma in experiments with solid targets.
- This regime plays a critical role in
  - proton acceleration;
  - generation of positron jets;
  - neutron generation (ultrashort source);
  - x-ray generation (bright, short source);



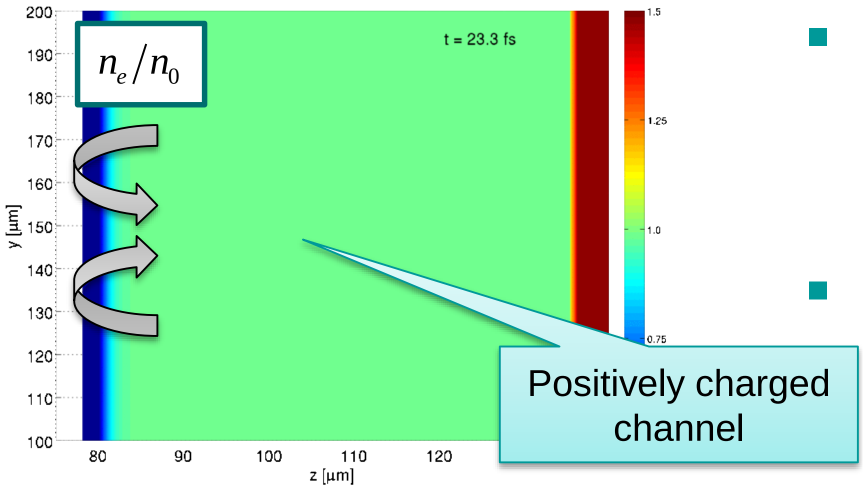
Positron production (S. Wilks)

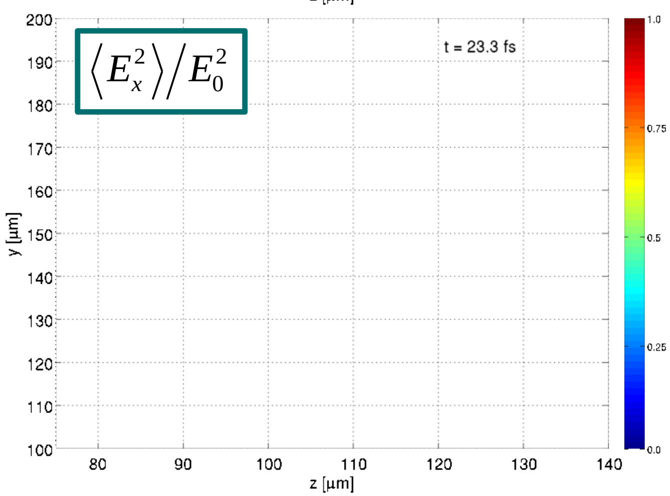


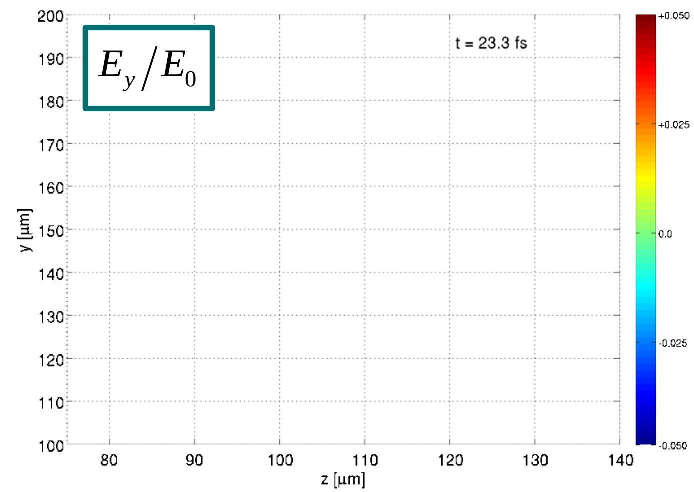
Neutron production (I. Pomerantz)

Channel formation in low-density plasma

- Laser beam expels electrons, creating an ion channel ($\tau >> 1/\omega_p$).
- Electrons are continuously injected into the channel near the opening.
- Electrons are radially confined, performing betatron oscillations while moving forward.
- The number of accelerated electrons is only limited by the channel expansion time.



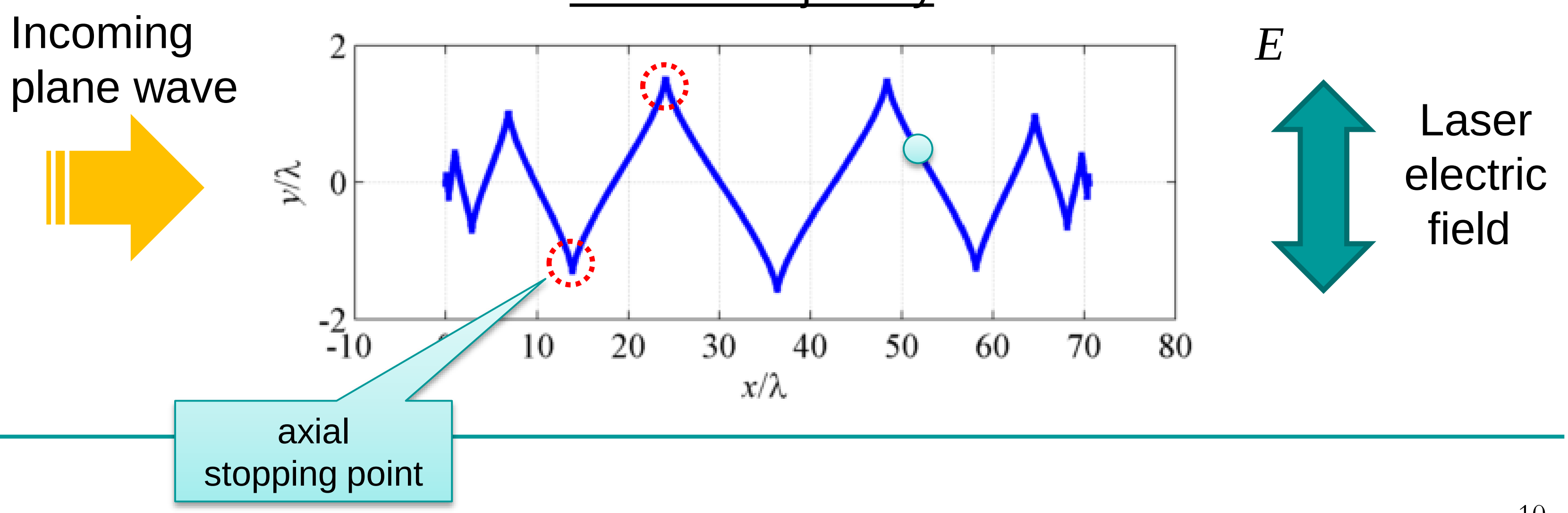




Vacuum motion at $a_0 >> 1$

- At $a_0 >> 1$, longitudinal acceleration by the Lorentz force is significant.
- Most of the energy is associated with the forward motion ($p_{\parallel}/p_{\perp} \approx a_0 \gg 1$).
- An upper limit on the γ-factor is $\gamma_{vac} = 1 + a_0^2/2$ (best case scenario).
- The energy gain inside a beam is lower due to the transverse expulsion.

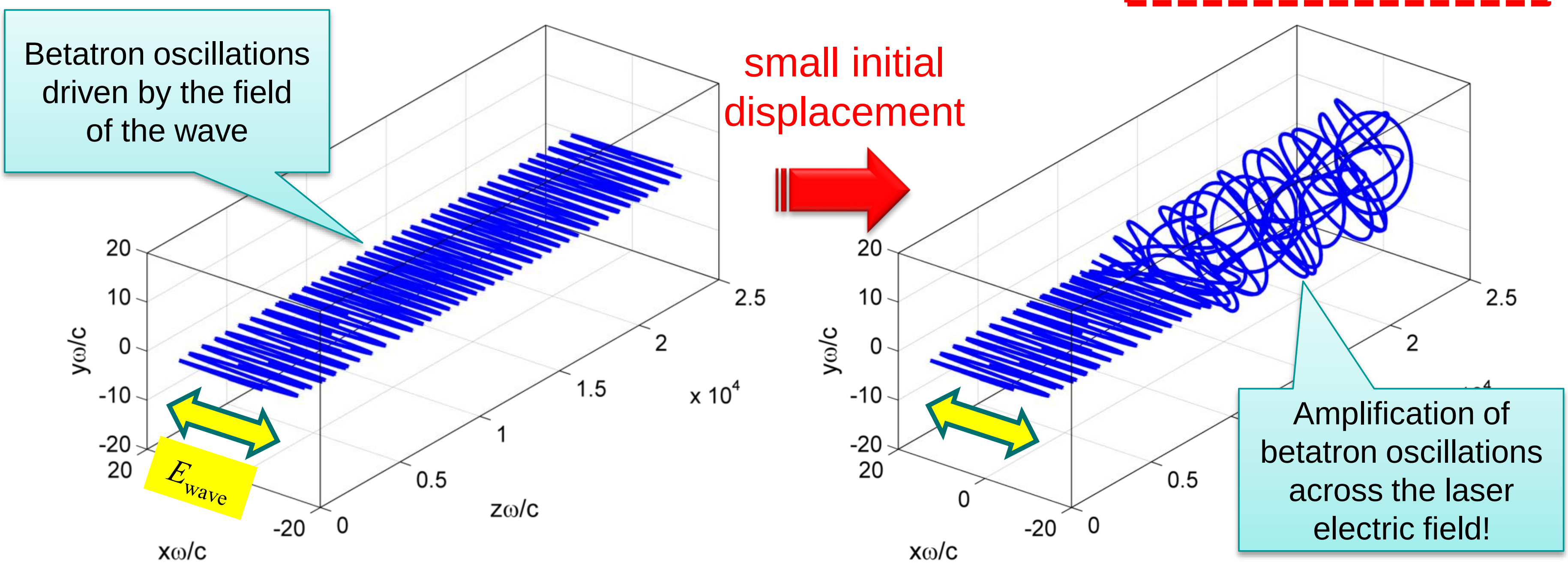
Electron trajectory



Motion in a channel at $a_0 >> 1$

- Is there a way to generate super-ponderomotive electrons ($\gamma > 1 + a_0^2/2$)?
- Can the accelerated electrons retain their energy?
- **Conventional understanding:** electron energy enhanc via the betatron resonance.

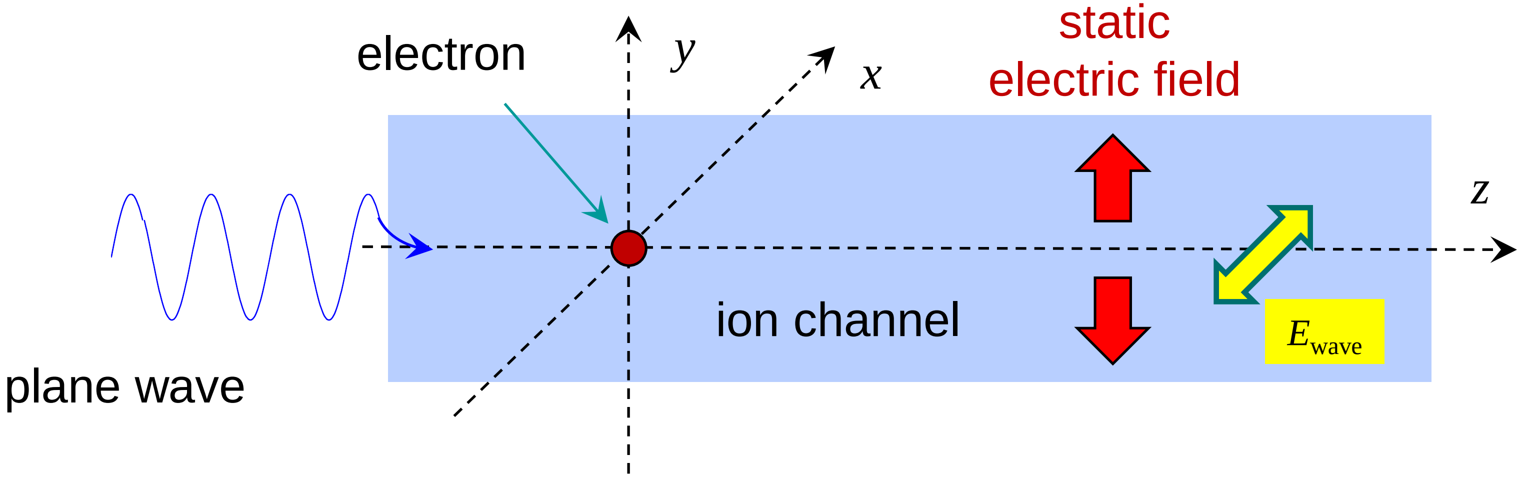
What physics is missing in the conventional picture?



Single-electron model in a 2D channel

- We decouple the electric field of the laser and the field of the channel by choosing a 2D spatial setup.

- Consider a case where the laser electric field is perpendicular to the field of the channel.



Main equations

The electron moves in a given static field of the channel and the oscillating field of the wave $a = a_0 \sin\left(\omega t - \omega z/c\right)$

$$\frac{d^2 y}{d\tau^2} + \gamma\omega_{p0}^2 y = 0$$

$$\frac{d}{d\tau}\left(\frac{p_z}{m_e c}\right) = \frac{1}{2}\frac{da^2}{d\xi}$$

$$\frac{d\xi}{d\tau} = \gamma - \frac{p_z}{m_e c}$$

$$\gamma \equiv \sqrt{1 + a^2 + \frac{1}{c^2}\left(\frac{dy}{d\tau}\right)^2 + \left(\frac{p_z}{m_e c}\right)^2}$$

$$\xi \equiv t - z/c$$

$$dt/d\tau = \gamma$$

Natural frequency is modulated at 2ω

- Betatron oscillations are coupled to the axial motion through γ.
- Axial motion in the wave strongly modulates γ even in vacuum.

Prior to significant amplification, the system reduces to

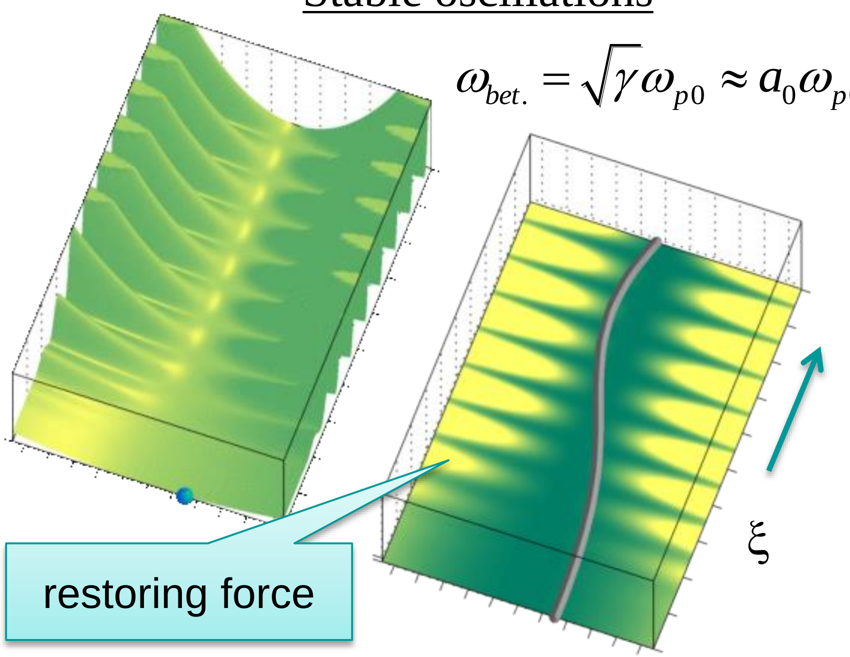
$$\frac{d^2 y}{d\tau^2} + \omega_{p0}^2\left[1 + \frac{a_0^2}{2}\sin^2\left(\omega\tau\right)\right] y = 0$$

Parametric amplification of oscillations

- Ultrarelativistic axial motion enhances the ion density in a co-moving frame.
- Axial acceleration and deceleration modulate the perceived ion density.
- Oscillations become unstable when the period of the modulations becomes comparable to the period of the betatron oscillations: $\omega_{bet.} \approx c/\lambda$

Stable oscillations

$$\omega_{bet.} = \sqrt{\gamma}\omega_{p0} \approx a_0\omega_{p0}$$



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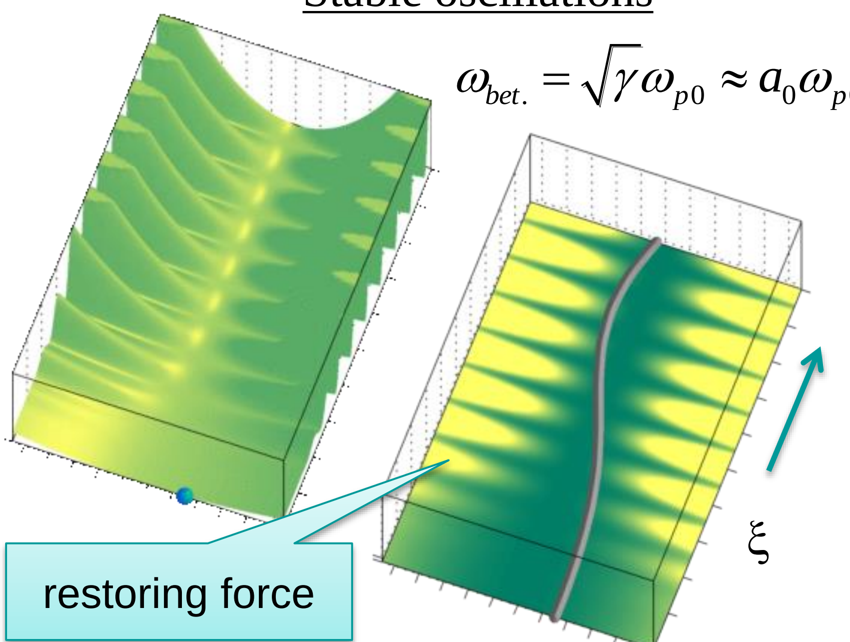
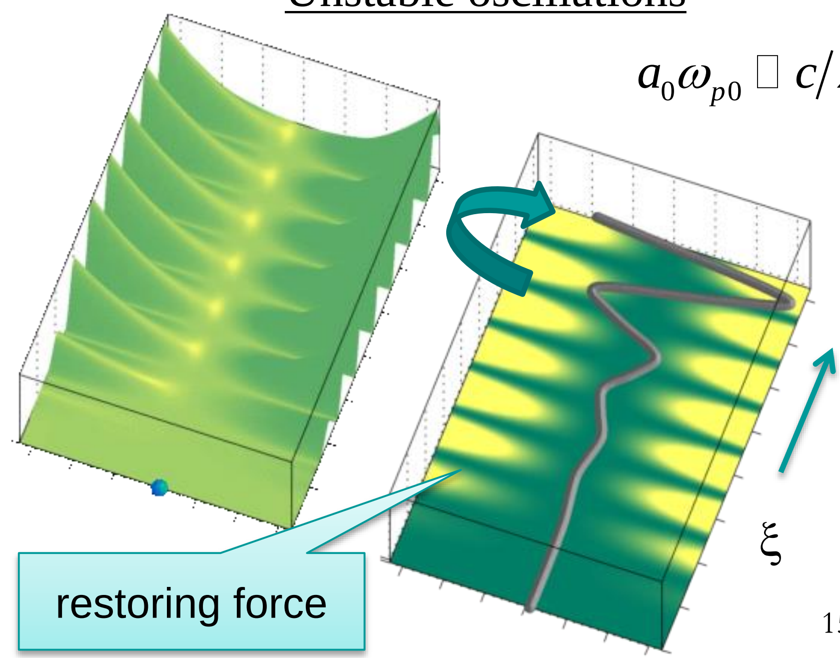


<u>Unstable oscillations</u>

$$a_0\omega_{p0} \,\square\, c/\lambda$$



Enhancement of axial acceleration

- The axial momentum gain is limited by the dephasing rate:

$$\frac{dp_z}{d\tau} = \frac{m_e c}{2}\frac{da^2}{d\xi}$$

wave pressure gradient

$$\frac{d\xi}{d\tau} = \gamma - p_z/m_e c$$

- There is an integral of motion:

$$I \equiv \gamma - \frac{p_z}{m_e c} + \frac{\omega_p^2}{c^2}\frac{y^2}{2}$$

dephasing

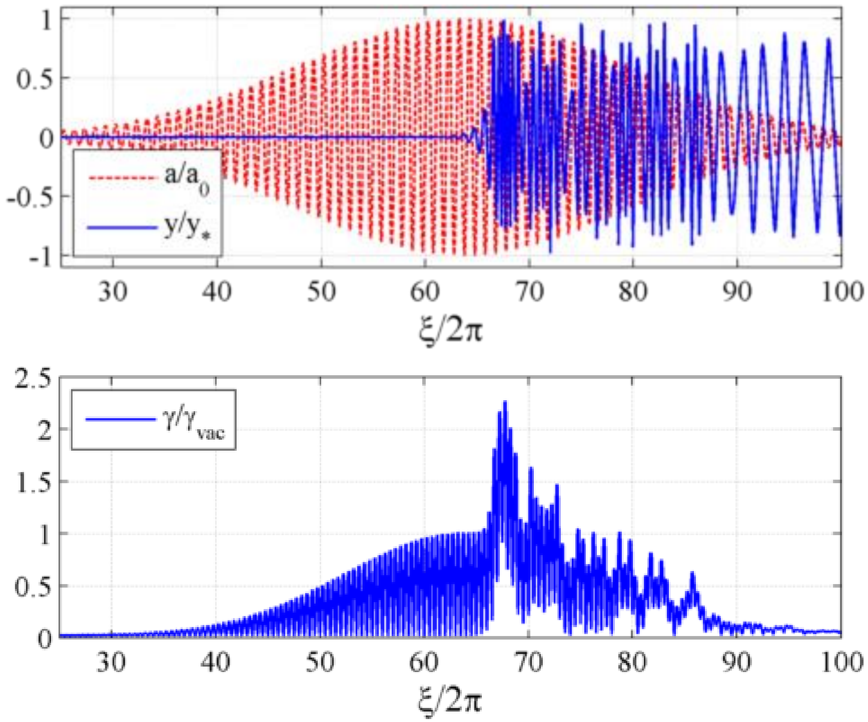
- The dephasing rate is constant in the vacuum case: $I = \gamma - \dfrac{p_z}{m_e c}$

- Amplification of betatron oscillations reduces the dephasing

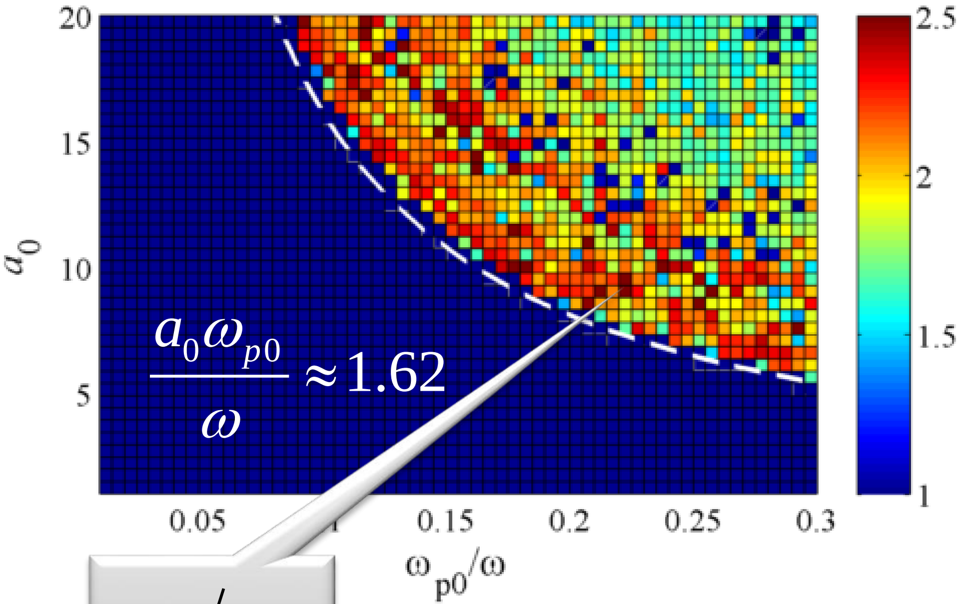
$$\gamma - \frac{p_z}{m_e c} = I - \frac{\omega_p^2}{c^2}\frac{y^2}{2}$$

Threshold for energy enhancement

Example of energy enhancement



Maximum γ-factor achieved by the electron



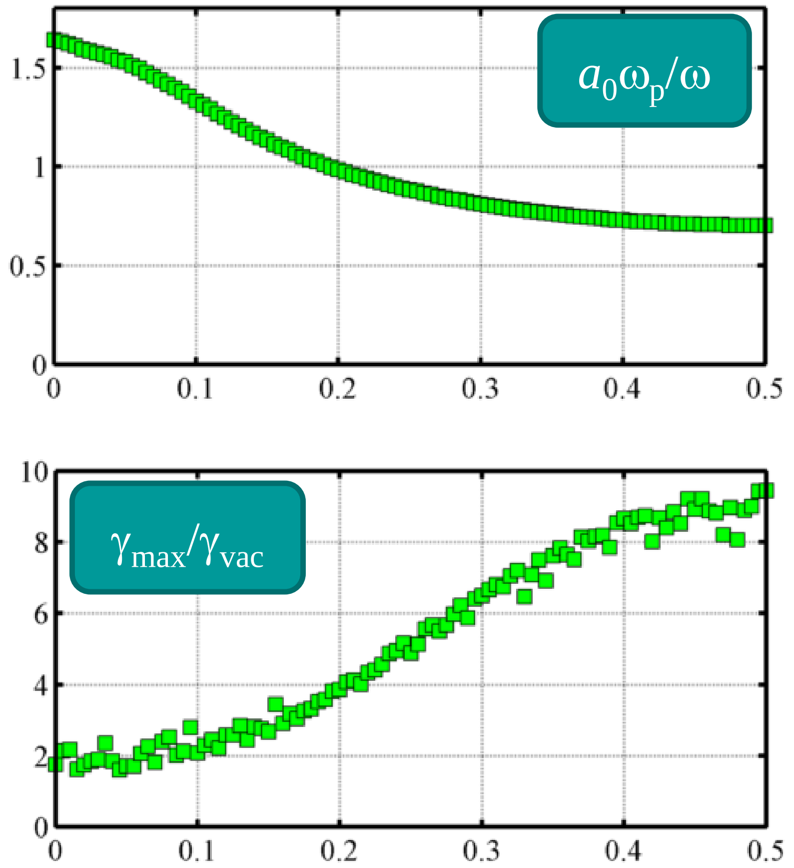
$$\frac{a_0 \omega_{p0}}{\omega} \approx 1.62$$

$$\gamma_{max}/\gamma_{vac}$$

$$\gamma_{vac} \equiv 1 + a_0^2/2$$

Phys. Rev. Lett. 108, 145004 (2012); Phys. Plasmas 21, 033104 (2014);

Effect of laser polarization



no driving field

θ/π

driving field across channel

- The effect is present regardless of the laser field orientation.
- The onset of the energy enhancement is determined by

$$a_0\omega_p/\omega$$

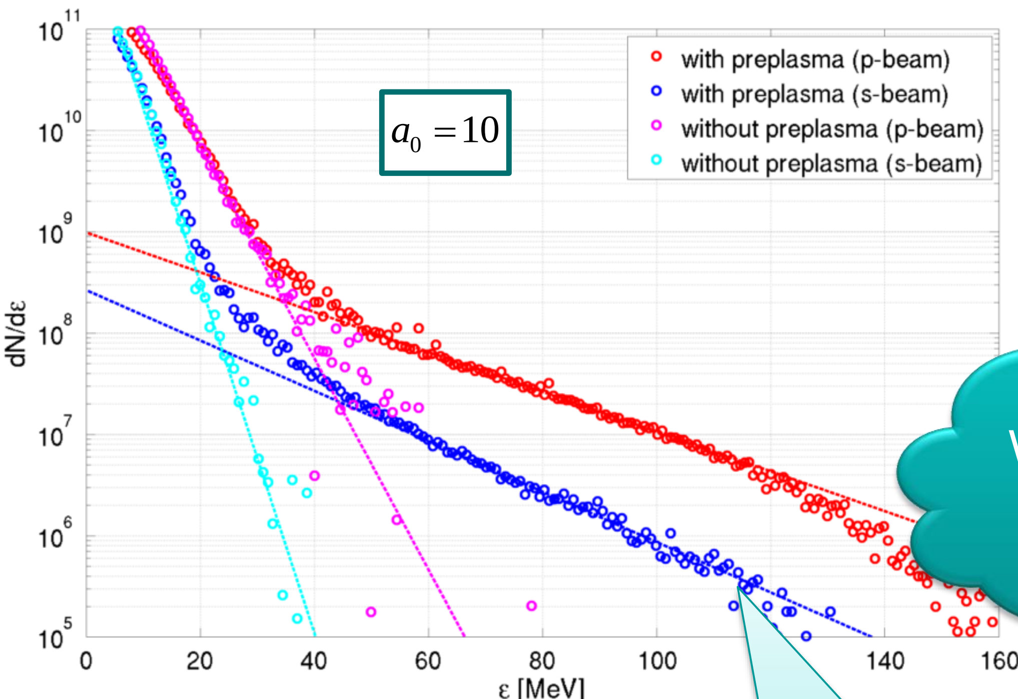
- The underlying mechanism is an instability and not a resonance.
- The enhancement occurs for a wide range of parameters above the threshold.

Key aspects of the parametric amplification (recap):

- axial motion induces a modulation in γ
- the modulation makes betatron oscillations unstable
- amplification of the oscillations reduces the dephasing
- reduced dephasing leads to energy enhancement

PIC simulations of electron heating

- We have performed 2D PIC simulations for a target with and without a 60 μm preplasma using the Plasma Simulation Code (PSC).



super-ponderomotive tail

Main observations

- There is a super-ponderomotive tail in the presence of the preplasma.

- ...e spectrum is ...he laser beam

What else might be missing?

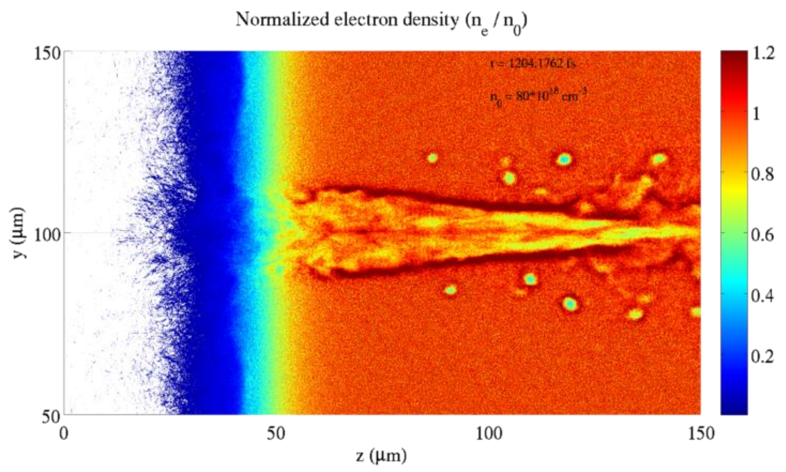
- The maximum electron energies exceed the analytical prediction.

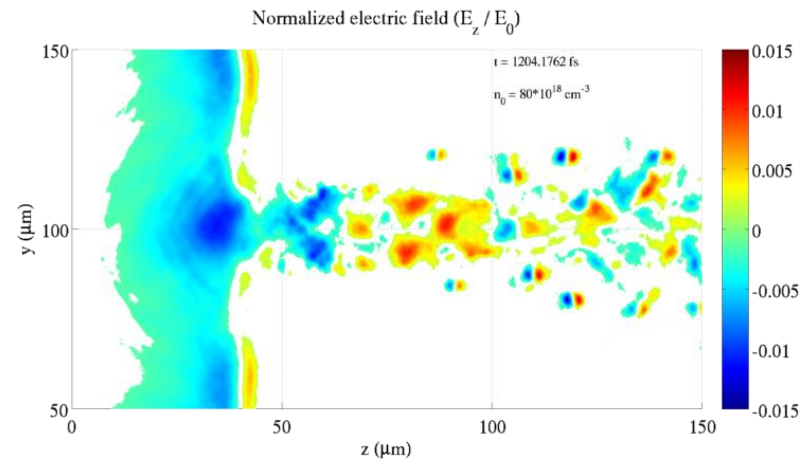
What key factors are affecting electron acceleration in a channel?

- Transverse quasistatic electric field inside the ion channel

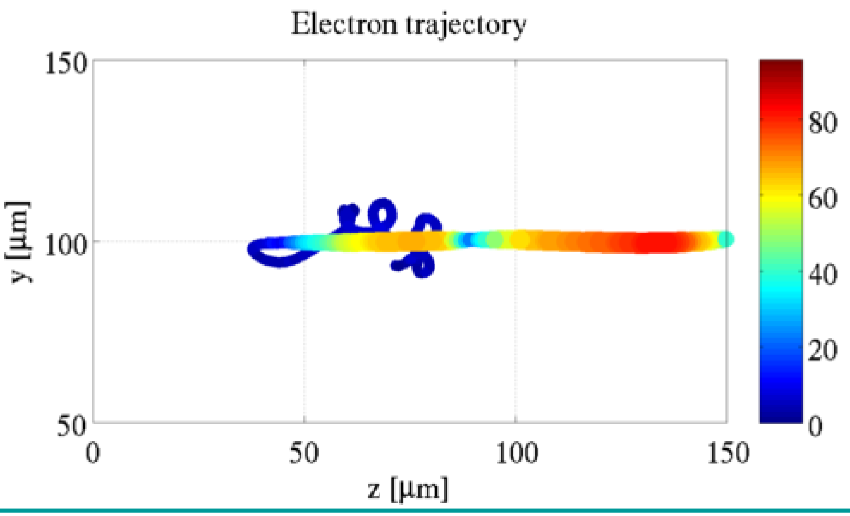
- Longitudinal quasistatic electric field at the entrance of the channel

Self-generated static axial field





- Static axial electric field is maintained at the entrance into the channel.
- Electrons pass through this region before being accelerated by the laser.



Effect of axial electric field

- Consider an electron accelerated in a vacuum by a plane wave that crosses a region with a weak axial electric field.

- <u>**Key findings:**</u>

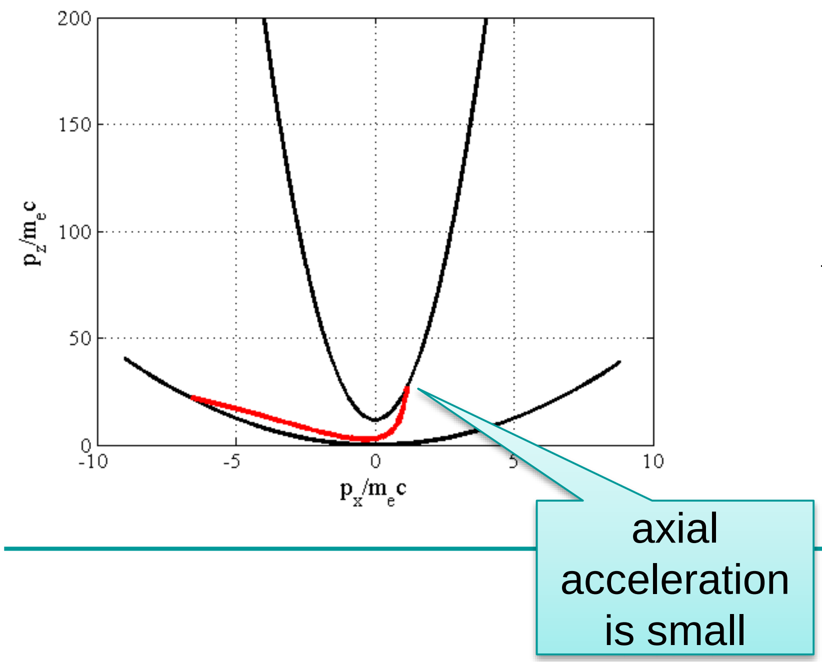
  - ✓ Axial electric field decreases the dephasing

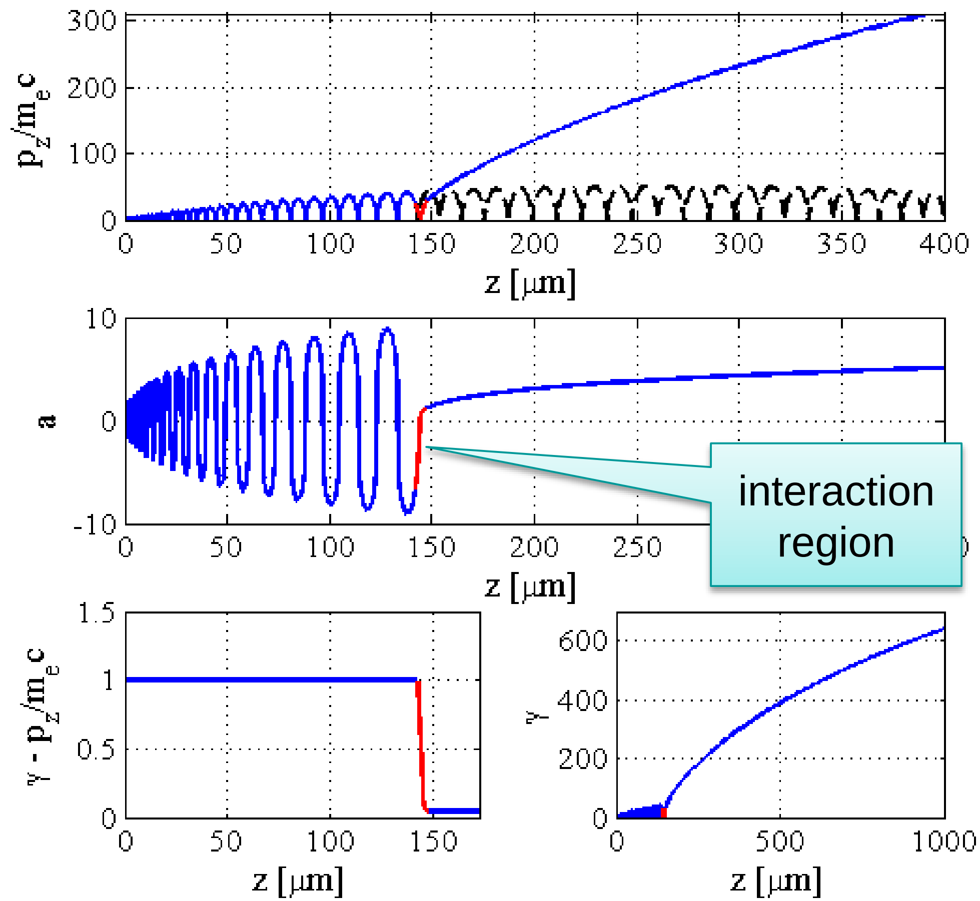
$$\frac{d}{d\xi}\left(\gamma - p_z / m_e c\right) = \frac{|e| E_{\parallel}}{m_e c}$$

  - ✓ This leads to energy enhancement by a factor of $\frac{\gamma_{\max}}{\gamma_{vac}} \approx \frac{2 p_*}{m_e c}$ where p_* is the axial momentum immediately after the interaction.

Super-ponderomotive electrons

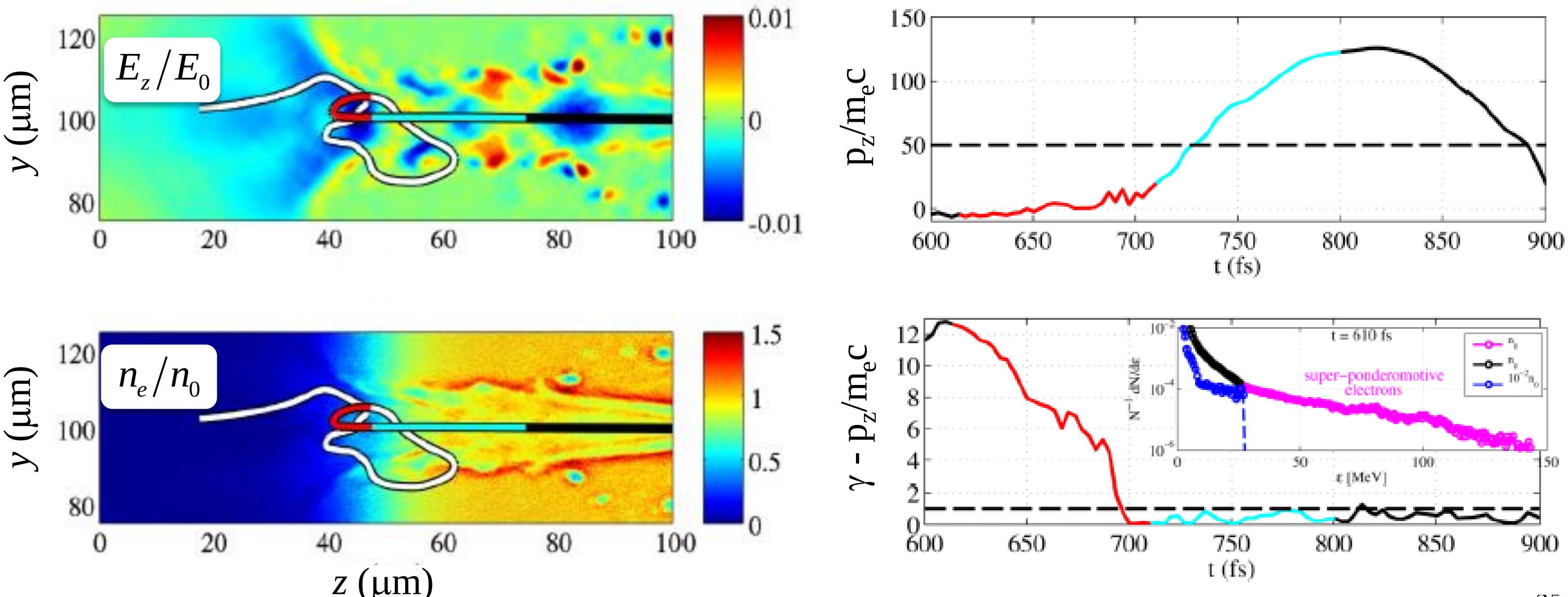
- Axial electric field launches electron onto a super-ponderomotive trajectory.
- Axial acceleration by the field is relatively small.





Self-consistently formed channel

- We have performed simulations for $n_0 = 7.2\times10^{-4} n_{cr}$ and $n_0 = 7.2\times10^{-2} n_{cr}$
- The total energy absorbed by electrons increases by a factor of 2×10^4.
- At lower density, the channel is fully evacuated and no electrons sample the axial field.



Phys. Rev. Lett. 111, 065002 (2013)

Role of a weak axial field (recap):

- axial electric field reduces the dephasing
- direct energy gain from the field is small
- subsequent interaction with the laser leads to a significant energy enhancement

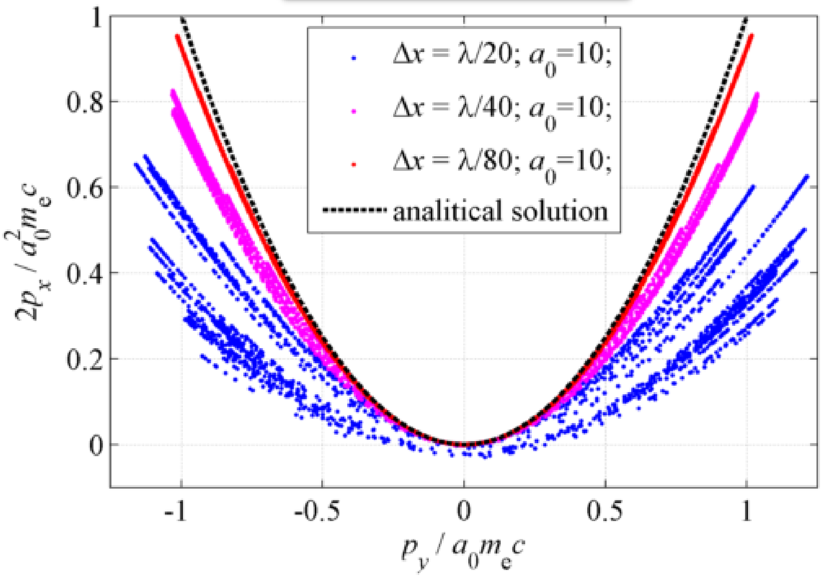
Simulation resolution constraints

- Particle-in-cell codes are often used for simulating this problem.
- Calculated electron spectra are sensitive to the resolution (spatial and temporal) even when the wave-length and the wave-period are well resolved.
- What resolution is needed to correctly reproduce the electron dynamics in these regimes?

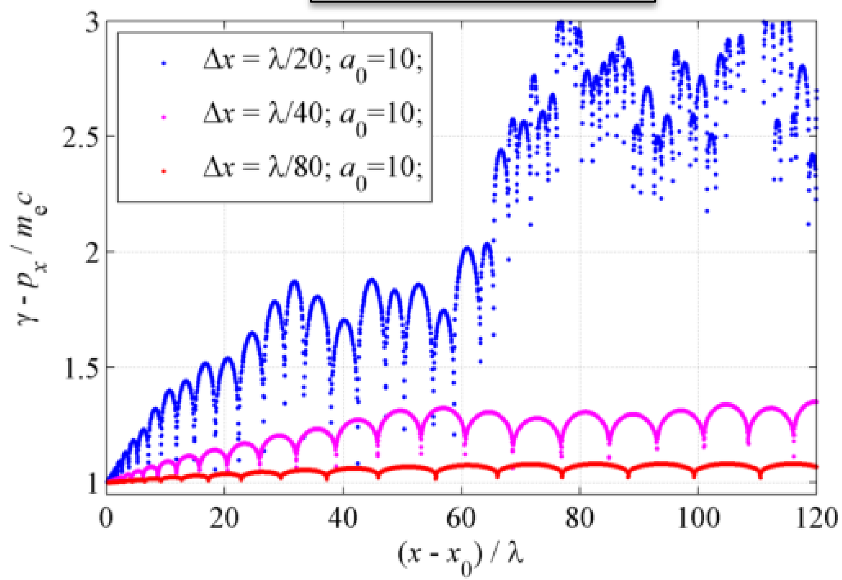
PIC particle tracking results

- The deviation from the analytical solution is considerable.
- The deviation becomes more severe for higher a_0.
- The errors in dephasing accumulate near the stopping points.

Phase space



Dephasing rate



Temporal resolution criterion

- The strongest acceleration is near a stopping point:

$$\Delta p / \Delta t \approx a_0 \omega m_e c$$

- The non-relativistic part of the trajectory is well resolved if

$$|\Delta p| \ll m_e c \quad \Rightarrow \quad \Delta t \ll 1/a_0 \omega$$

- At the stopping point, errors in momentum comparable to $m_e c$ lead to a considerable change in the dephasing rate.

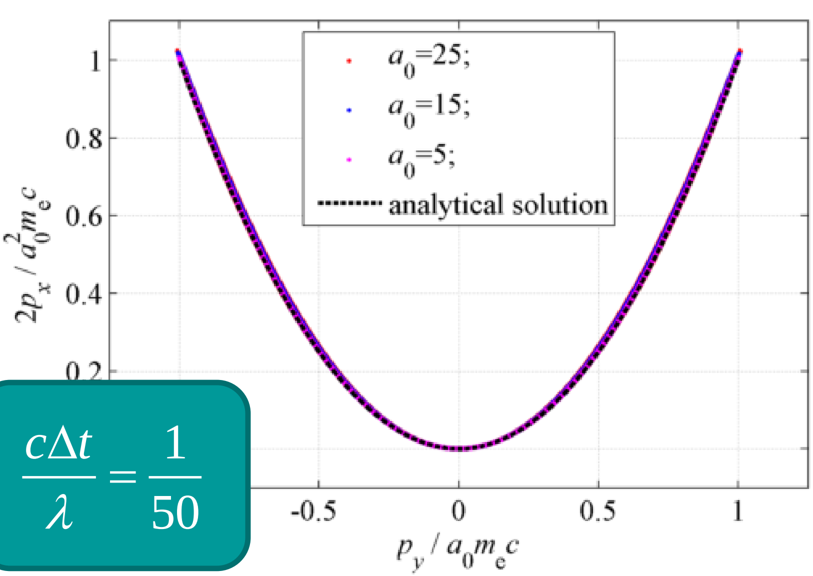
- This effect is similar to pre-acceleration and leads to significant changes in subsequent acceleration.

Phys. Rev. Lett. 111, 065002 (2013)

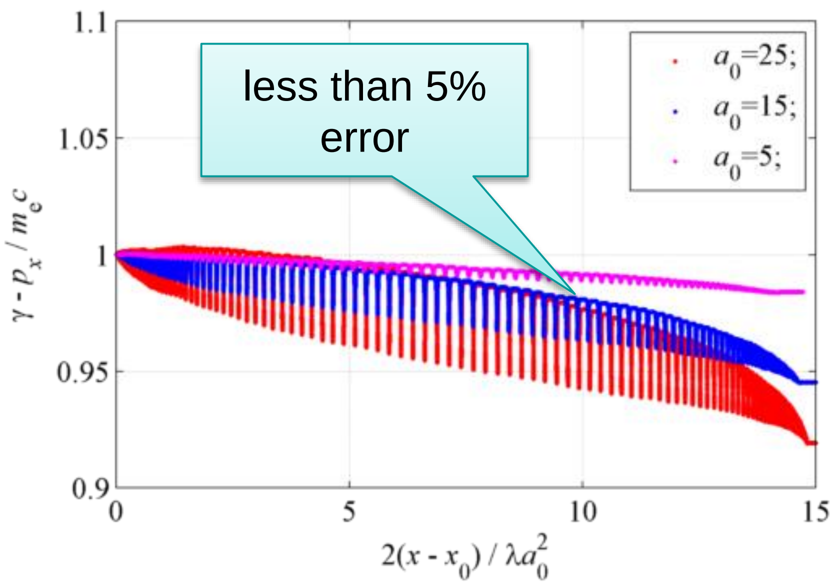
Particle pusher sub-cycling

arXiv:1410.8491

- Within the particle pusher, the error occurs due to significant rotation of the electron momentum caused by strong acceleration.
- We introduce a critical rotation angle and reduce the time-step if the rotation angle is too large.
- The sub-cycling is efficient, since it affects only vicinities of stopping points.



$$\frac{c\Delta t}{\lambda} = \frac{1}{50}$$



Summary

- Electron interactions with transverse and longitudinal electric fields of the channel can lead to super-ponderomotive energies.

- In the case of the transverse field, the effect results from parametric amplification of the betraton oscillations.

  Phys. Rev. Lett. 108, 145004 (2012)
  Phys. Plasmas 21, 033104 (2014)

- In the case of the axial field, the effect results from a direct reduction of the dephasing by the static field and this mechanism is complementary to the parametric amplification.

  Phys. Rev. Lett. 111, 065002 (2013)

- The temporal resolution in PIC simulations must be significantly less than $1/a_0\omega$ to correctly reproduce these effects.

  arXiv:1410.8491

Conclusions

- Prepulse can play a significant role in determining the performance of the secondary particle sources.
- Preplasma must be well characterized for a reliable interpretation of experimental results.
- The next step is to optimize the preplasma based on the application (proton acceleration, positron production).
- It might be possible to produce a desired "preplasma" in a two pulse set-up or by using an additional medium.