Particle-in-Cell Simulations of Particle Acceleration

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Previous analytical calculations suggest that a preaccelerated test particle can be ponderomotively accelerated to energies in excess of 100 MeV by an intense electromagnetic pulse propagating in a underdense plasma.[1] To check these predictions we have developed a relativistic, two-dimensional particle-in-cell code. Test simulations that validate the code will be described in detail. Preliminary simulations of the interaction of a preaccelerated electron bunch with an electromagnetic pulse in a plasma will be presented. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority.

1. C. J. McKinstrie and E. A. Startsev, Phys. Rev. E **54**, R1070 (1996); **56**, 2130 (1997).

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Abstract

Previous analytical calculations suggest that a preaccelerated test particle can be ponderomotively accelerated to energies in excess of 100 MeV by an intense electromagnetic pulse propagating in an underdense pasma.[1] To check these predictions we have developed a relativistic, two-dimensional particle-in-cell code. Test simulations that validate the code will be described in detail. Preliminary simulations of the interaction of a preaccelerated electron bunch with an electromagnetic pulse in a plasma will be presented.

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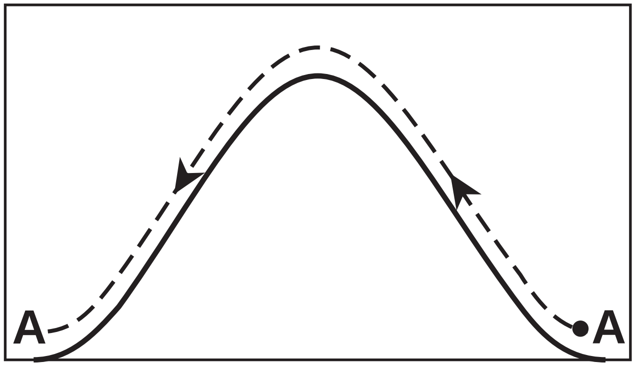
An intense laser pulse in a plasma repels the particle

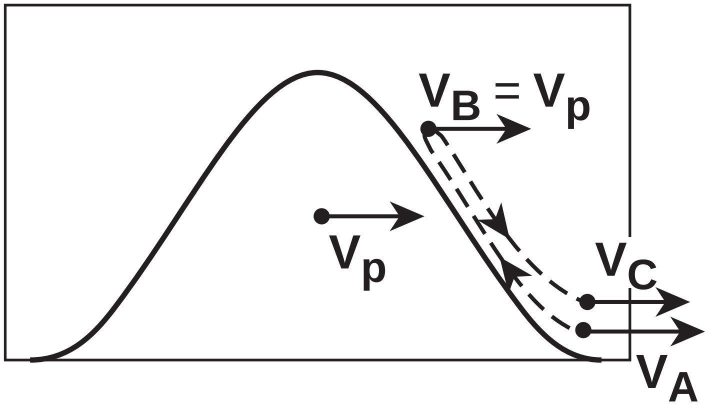
- **In vacuum the pulse displaces the particle but leaves it at rest.**



- **In a plasma the pulse repels the particle if intensity exceeds a threshold**

$$a_B^2 = 2\left[\left(\gamma_p\gamma_A - u_p u_A\right)^2 - 1\right].$$

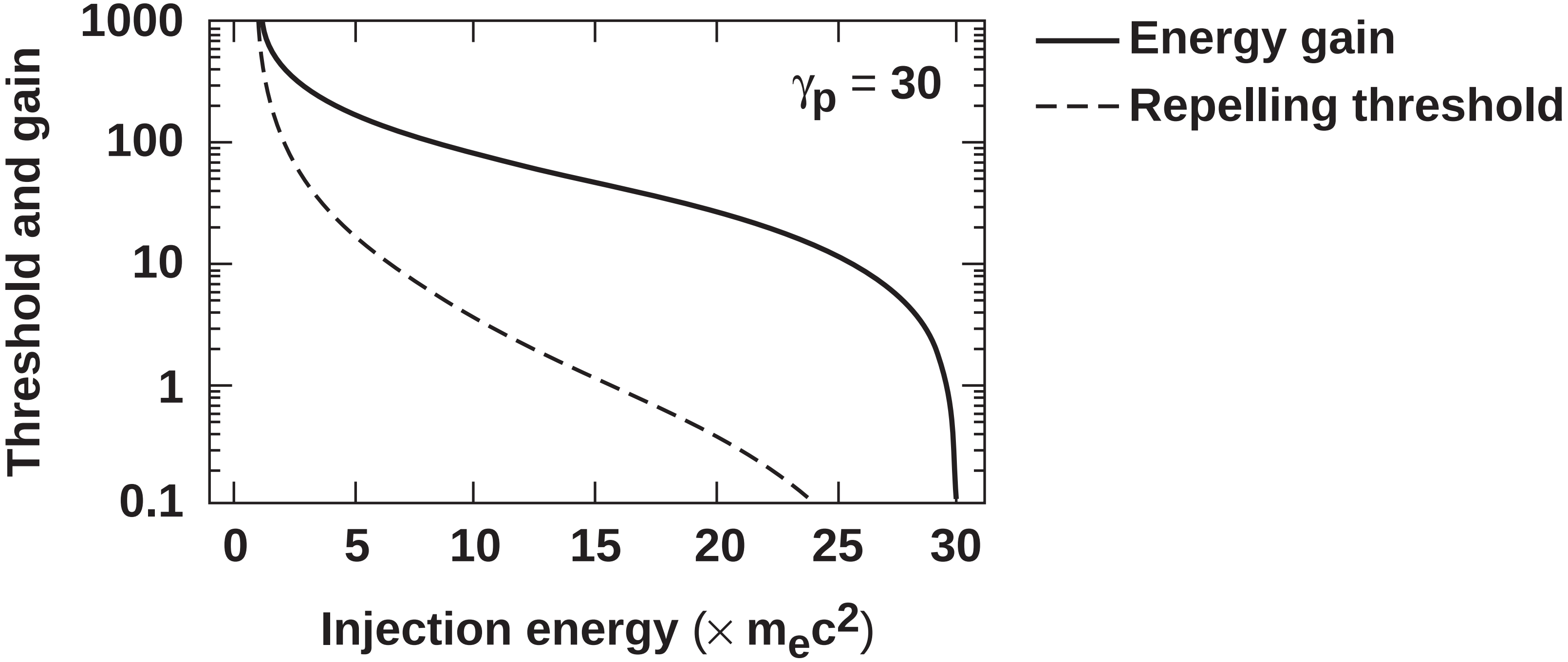
where $a_B = e|A|m_e c^2$



- **Here,** $\gamma_g = 1/\left(1 - v_g^2\right)^{1/2}$ **and** $u_p = \left(\gamma_p^2 - 1\right)^{1/2}$.

The particle can be effectively accelerated

- The energy gain $\delta\gamma = 2\left(u_p^2\,\gamma_A - \gamma_p\,u_p\,u_A\right)$.



- With energy measured in units of the particle rest mass, if the injection energy $\gamma_A = 7.0$, the repelling threshold $a_B^2 = 8.3$ and the energy gain $\delta\gamma = 120$.

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1-D simulations show good agreement with theory[1, 2]

- 1-D propagation of an intense circularly polarized laser pulse in a plasma is described by the equations

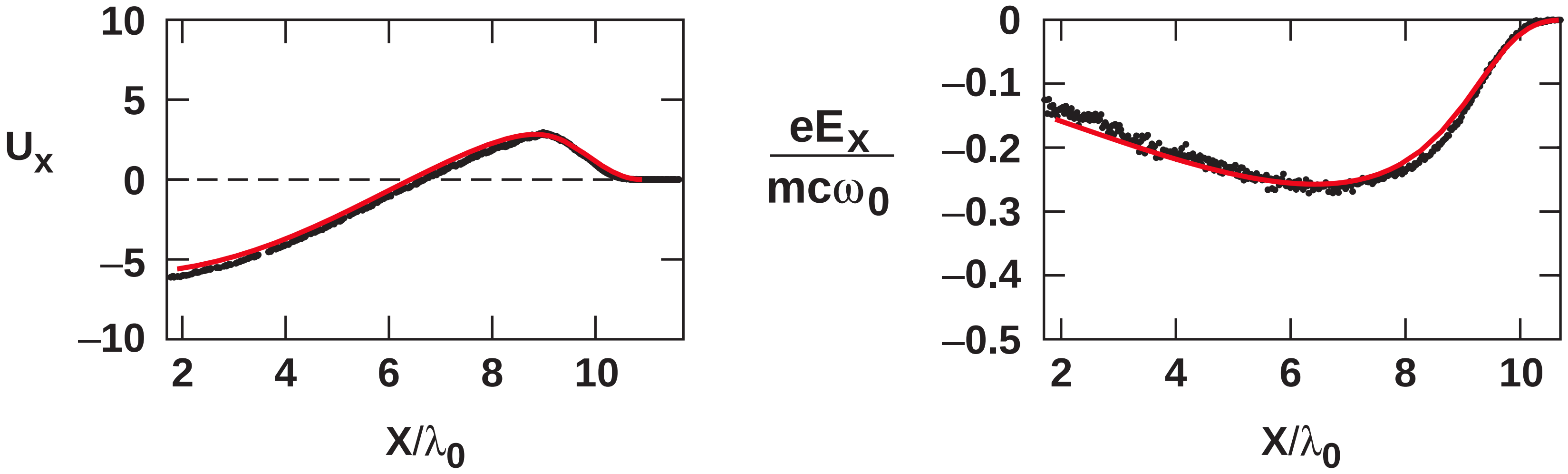
$$u_x = \left[v_g \bullet (1+\phi) - \psi\right] \Big/ \left(1 - v_g^2\right),$$

$$\phi'' = (2\pi)^2 \left[1 - v_g \bullet (1+\phi)/\psi\right],$$

$$\psi = \left[\left(1+\phi^2\right) - \left(1 - v_g^2\right) \bullet \left(1 + a^2\right)\right]^{1/2},$$

where $\phi = e\varphi/mc^2$ is electrostatic potential, v_g is pulse group speed, and $a = eA/mc^2$.

- The fluid and PIC results were compared for $a = 5 \bullet \sin(\pi x/9)$, $\omega_p/\omega_0 = 0.1$.



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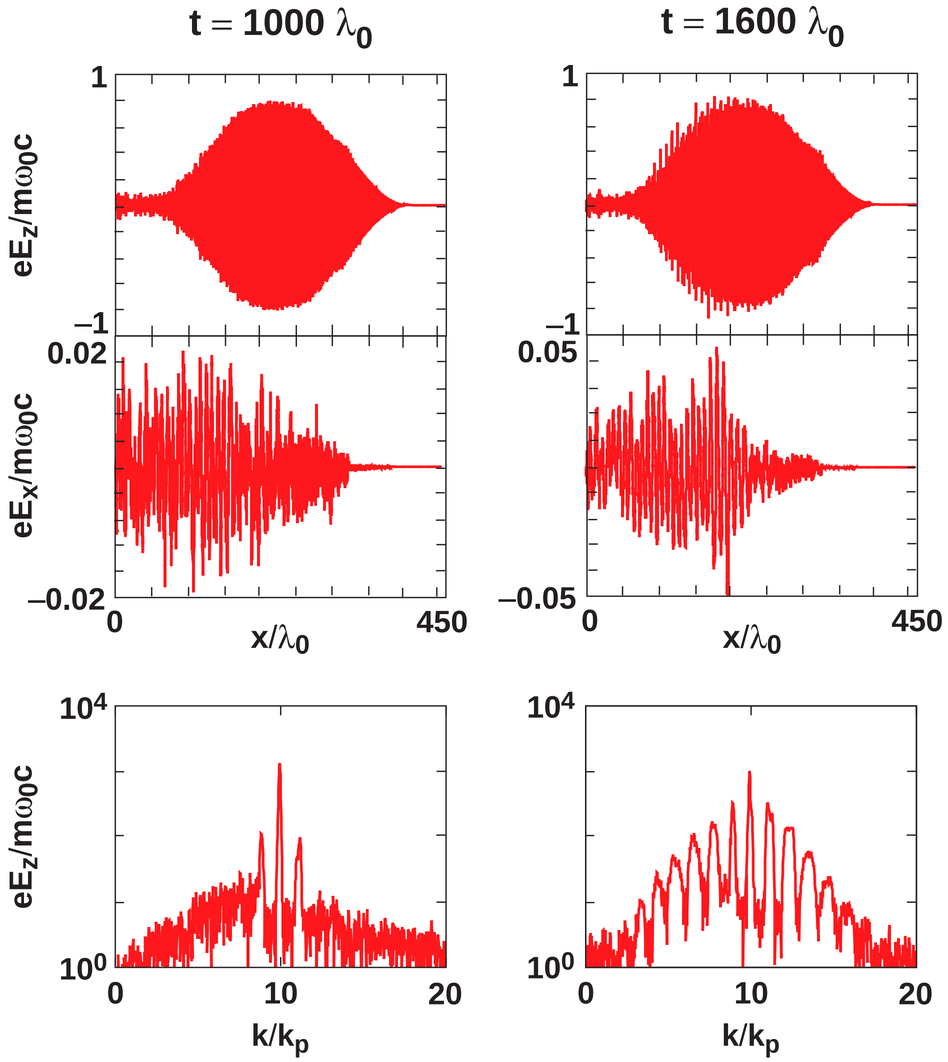
2. P. K. Kaw, A. Sen and T. Katsouleas, Phys. Rev. Lett. 68, 3172 (1992).

Forward SRS was observed

- **The 1-D simulation with $a_0 = 0.8$, $\omega_0/\omega_p = 10$, $l = 200\ \lambda_0$, $\lambda_0 = 1\ \mu$m, and linear polarization.**

- **At $t = 1000\ \lambda_0$ RFS grows at the head of the pulse from anomalously large noise source provided by RBS.**

- **At $t = 1600\ \lambda_0$ the nonlinear state of the beam evolution leads to spectral cascading[3].**



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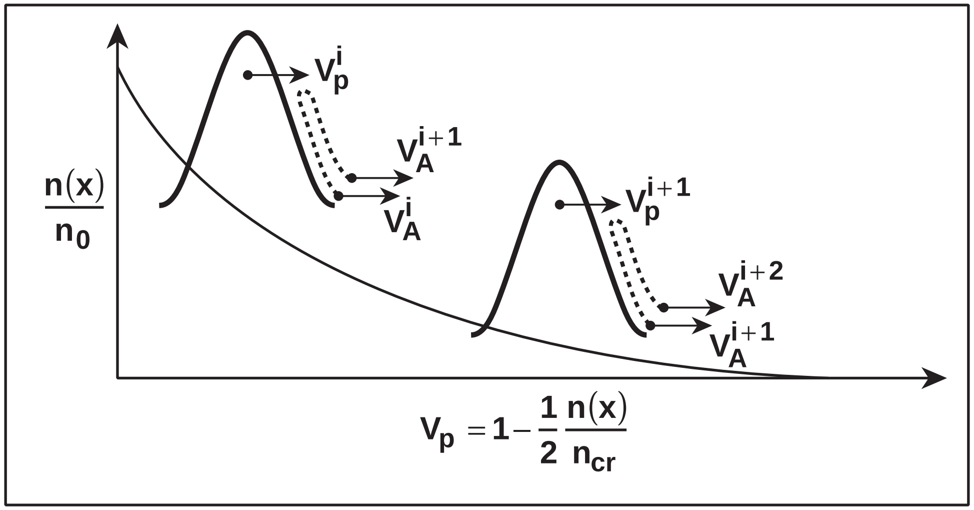
[3] C. D. Decker, W. B. Mori, and T. Katsouleas, Phys. Rev. E, 50, R3338 (1994).

Multistage ponderomotive acceleration is possible in a plasma with a density gradient



- On each stage $\gamma_A^{i+1} = \gamma_A^i \left(\frac{\gamma_p^i}{\gamma_A^i}\right)^2$, where i denotes quantities before acceleration and i + 1 denotes quantities after acceleration.
- Also, the threshold for each stage is

$$\sqrt{1 + \frac{a_i^2}{2}} = \frac{1}{2}\left(\frac{\gamma_p^i}{\gamma_A^i} + \frac{\gamma_A^i}{\gamma_p^i}\right).$$

- If, on each stage, $\gamma_p^i / \gamma_A^i = \alpha = \text{const}$, then $a_i^{th} = \text{const}$ and the final energy after N stages is $\gamma_A^{final} = \alpha^{2N} \bullet \gamma_A^0$.

- If the density profile is chosen as $n(x) = n_0/(1 + x/l)^2$, then

$$\gamma_p^{i+1} / \gamma_p^i = \alpha^2 \quad \text{and} \quad \frac{\gamma_p^{i+1}}{\gamma_A^{i+1}} = \frac{\gamma_p^i}{\gamma_A^i} = \alpha = \text{const}.$$

- On the distance L, these will be

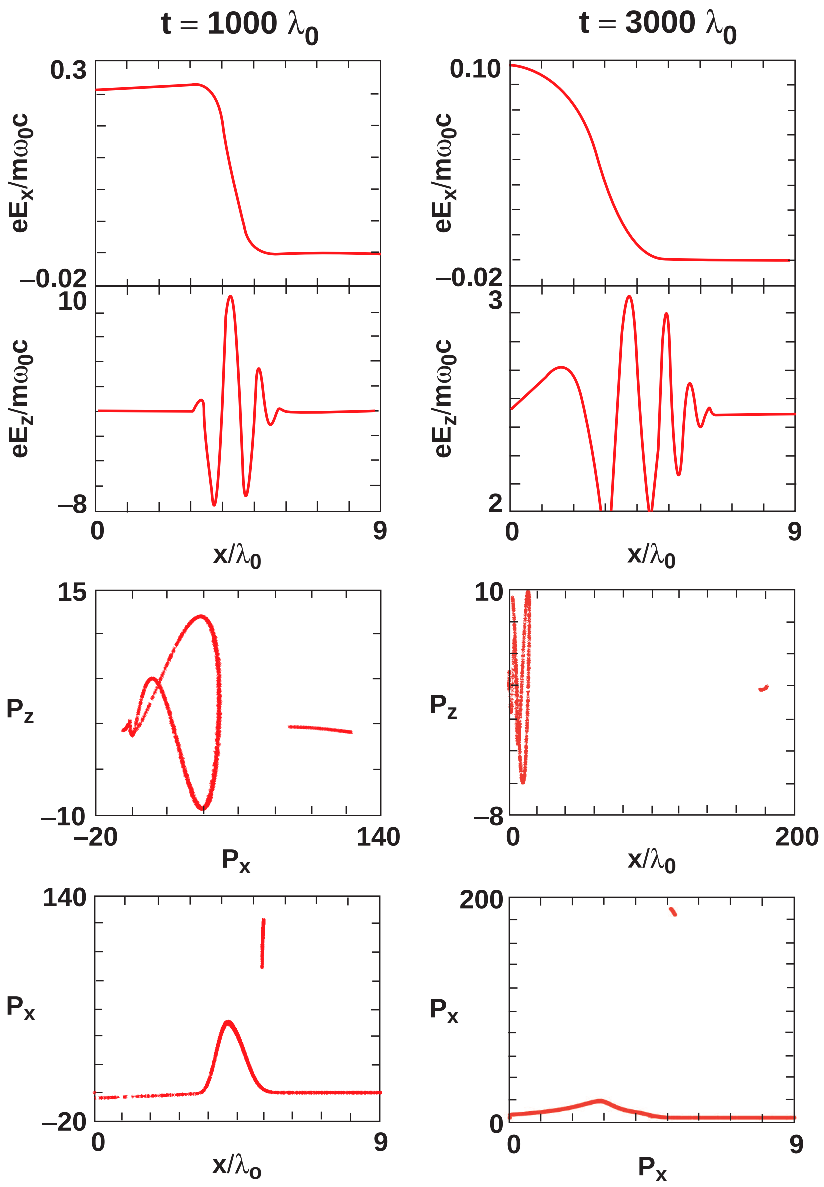
$$N = \frac{1}{2}\frac{\ln(1 + L/l)}{\ln\left(\gamma_p^0/\gamma_A^0\right)}$$ number of stages;

here, $\gamma_p^0 = \omega_0/\omega_p$.

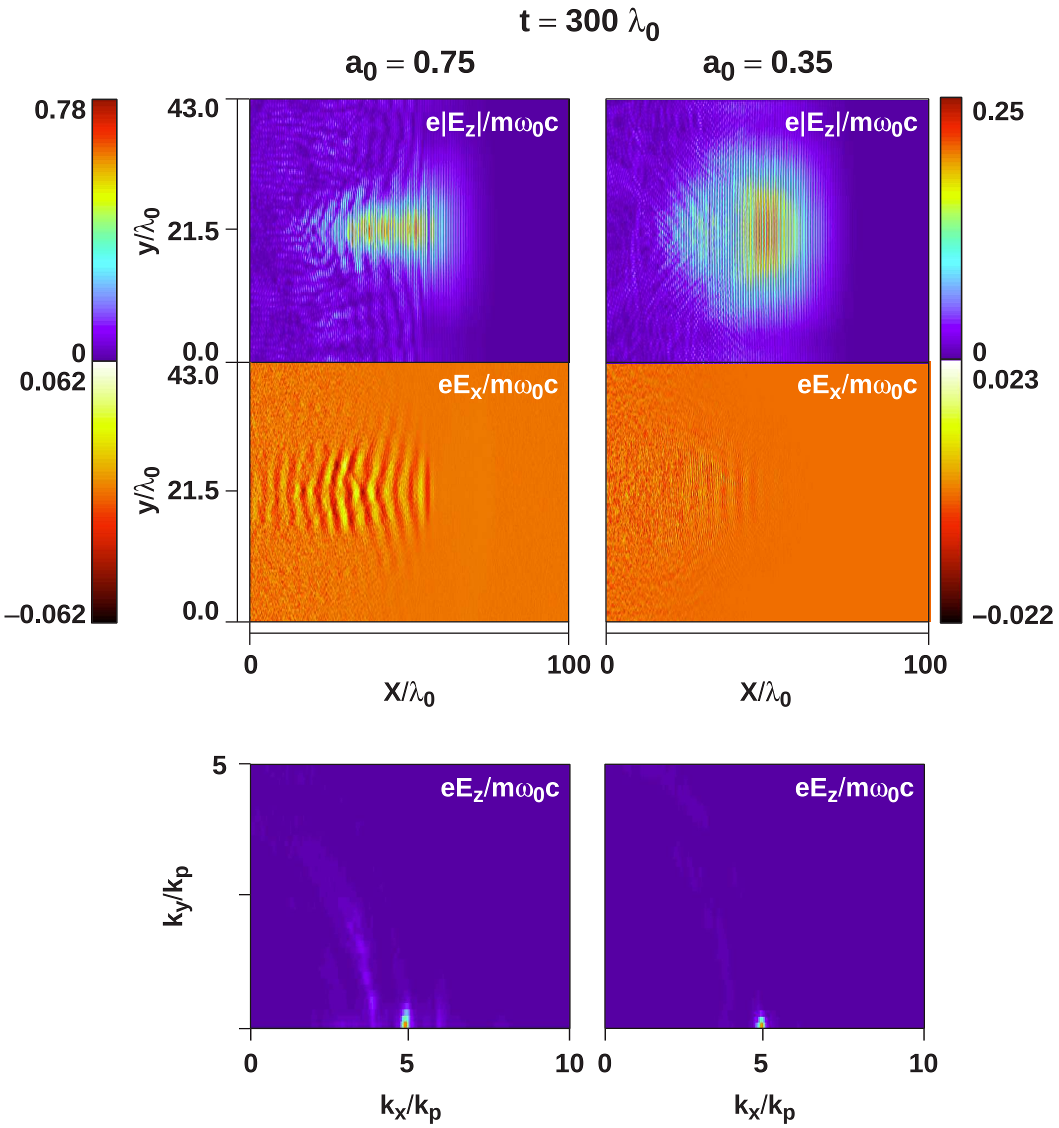
- If L/l = 1000, γ_A^0 = 5, ω_0/ω_p = 10, then N = 5 and γ_A^{final} = 5000 $m_e \bullet c^i$ = 2.5 GeV!

Accelerated particles were observed

- A bunch of electrons was preinjected ahead of the pulse in the direction of the pulse propagation with initial energies $\gamma_0 = 7$.
- Pulse intensity $a = 10$ and plasma density $\gamma_p = \omega_0/\omega_p = 30$, $l = 3\ \lambda_0$. Pulse was circularly polarized.
- At the time $t \sim \gamma_p^2 \bullet l \sim 3000\ \lambda_0$, preinjected particles have completed their acceleration and are moving ahead of the pulse.
- Energy gain $\delta\gamma = (\gamma_p/\gamma_0)^2 \bullet \gamma_0 \sim 130$ was observed.

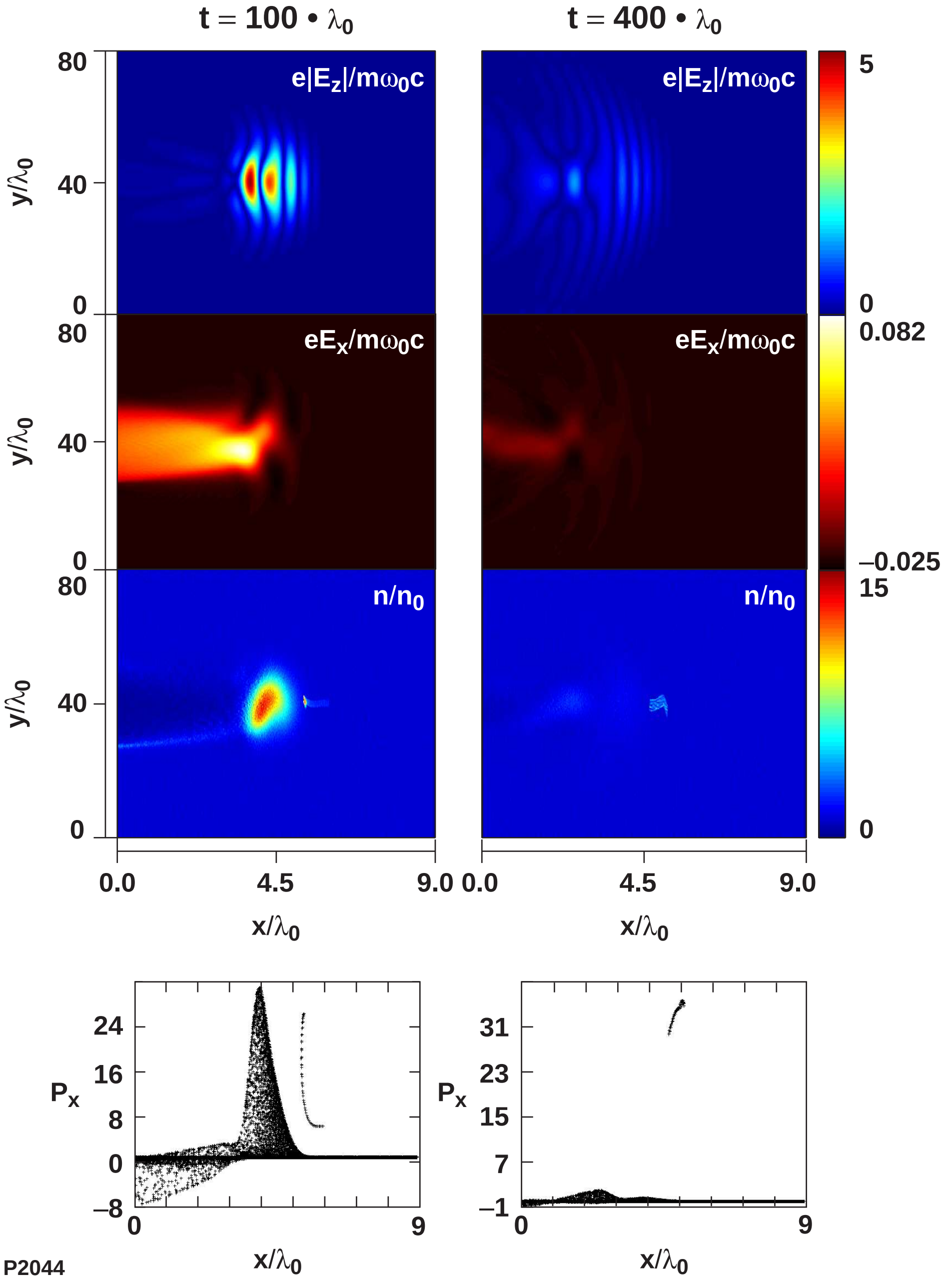


Relativistic self-focusing was observed for a pulse with $P > P_c$



- The 2-D simulations were made with the parameters (a) $a_0 = 0.75$, b) $a_0 = 0.35$, $\omega_0/\omega_p = 5$, $l = 40\ \lambda_0$, $r_\perp = 7\ \lambda_0$, $\lambda_0 = 1\ \mu m$.
- For these parameters $L_R = \pi \bullet r_\perp^2/\lambda_0 = 150 \bullet \lambda_0$, (a) $P/P_c = 2$, (b) $P/P_c = 0.5$.
- In the case of $P/P_c = 2$ beam stays focused for two Rayleigh lengths.
- Substantial Raman sidescatter (RSS) was present.
- RSS has only a downshifted Stokes component because the anti-Stokes cannot be simultaneously resonant.
- In comparison, for (b) $P/P_c = 0.5$, no self focusing was observed.

Electrostatic field does not prevent particle acceleration



- 2-D simulation of the particle acceleration was conducted with parameters $a_0 = 10$, $\omega_0/\omega_p = 10$, $r_\perp/\lambda_0 = 10$, $l/\lambda_0 = 3$.

$$L_R/\lambda_0 = \pi\,(r_\perp/\lambda_0)^2 \approx 300.$$

- The power of the pulse is being quickly depleted by the wake generation.

- Though the electrostatic field is significant, it is negligible ahead of the pulse where particles are accelerated.

- The initial particle energy was $\gamma_0 = 5$. The energy gain $\delta\gamma = 25$ was observed.

- Particles are spread in transverse direction by the ponderomotive force in the angle

$$\theta = \frac{\left|\Delta p_\perp^{\max}\right|}{\gamma^{\max}} = 0.01$$

Summary/Conclusion

- A simple 1-D acceleration scheme was suggested that uses the PM force to accelerate preinjected electrons to energies as high as 100 MeV.
- The model of the multistage pondermotive acceleration in a plasma with a density profile predicts energy gains of $\delta\gamma$. 2 GeV on a distance of several centimeters.
- This scheme relies on the fact that the group speed of the laser pulse is less than c.
- A 2-D particle-in-cell code was developed to check this prediction.
- Test simulations that validate the code were presented.
- Simulations of the interaction of a preaccelerated electron bunch with an electromagnetic pulse in a plasma show evidence of electron acceleration.