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Relativistic Multistage Laser Ion Acceleration

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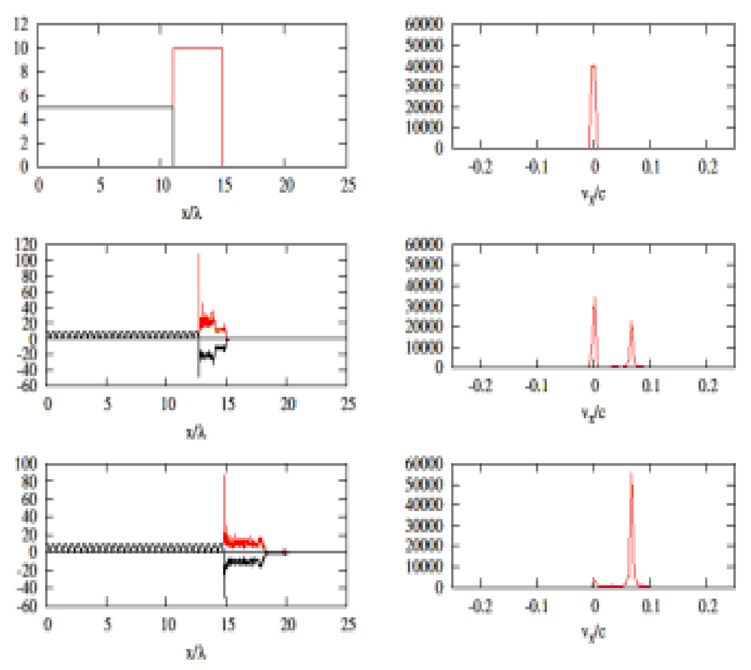
Introduction

- A relativistic calculation to determine the ion velocity and energy of second stage of ion acceleration has been done.
- A fully relativistic 1D3V PIC simulation using LPIC++ has been done.
- Results from PIC simulations validate our relativistic calculation for multistage acceleration.
- It has been found that relativistic results differ a lot from non-relativistic calculations at higher intensities and hence is inevitable.
- Further, 3D PIC simulations are performed to establish the feasibility of this process.

Acceleration Process



1D3V PIC simulations using LPIC++ showing acceleration of plasma ions using circularly polarized laser pulse.

The Model

- We consider a 1D situation where a beam of light of constant intensity I is driving into a plasma of uniform density and one ion species.
- It is assumed that the plasma is collisionless and that the light beam is completely reflected at the plasma surface.
- The steady state of this system can be found by examining the momentum balance in the instantaneous rest frame (IRF).
- The reflected light from a moving surface is doppler shifted and hence the ratio of intensity in IRF and lab frame is given by,

$$\frac{I^{IRF}}{I} = \frac{1-\beta_f}{1+\beta_f} \quad (1)$$

- The momentum balance in the IRF of plasma surface is given by,

$$2\frac{I}{c}\frac{1-\beta_f}{1+\beta_f} = 2\gamma_f^2 m_i n_i v_f^2 \quad (2)$$

- Algebraically solving for β_f, we get

$$\beta_f = \frac{\sqrt{\Xi}}{1+\sqrt{\Xi}}; \quad \Xi = \frac{I}{\rho c^3} \quad (3)$$

- This is the velocity with which the double layer moves through the plasma.
- The ion velocity in the lab frame v_i can be calculated using relativistic velocity addition.
- The time required for entire plasma slab to attain velocity v_i is

$$t = \frac{L}{v_f} \quad (4)$$

- We define the lab frame as K and the frame moving with velocity v_i as K'.
- The incident laser intensity in frame K' can be given by,

$$I' = I\frac{1-v_i/c}{1+v_i/c} \quad (5)$$

- With this new intensity the surface velocity v_f' turns out to be,

$$\beta_f' = \frac{v_f'}{c} = \frac{\sqrt{\Xi'}}{1+\sqrt{\Xi'}}; \quad \Xi' = \frac{I'}{\rho c^3} \quad (6)$$

- The ion velocity in frame K' turns out to be,

$$\frac{v_i'}{c} = \frac{2\beta_f'}{1+\beta_f'} \quad (7)$$

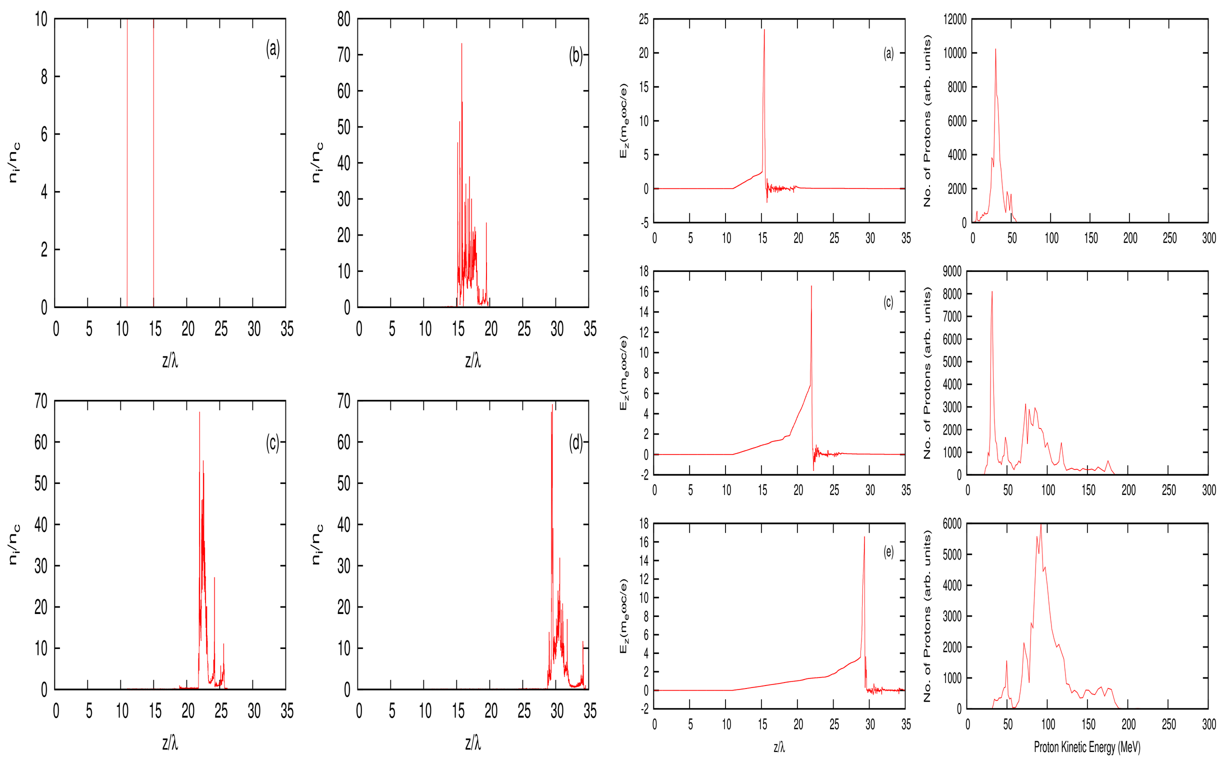
- The ion velocity in the lab frame after the second stage can be obtained using relativistic velocity addition.

$$\beta_{i2} = \frac{\beta_i + \beta_i'}{1+\beta_i\beta_i'} \quad (8)$$

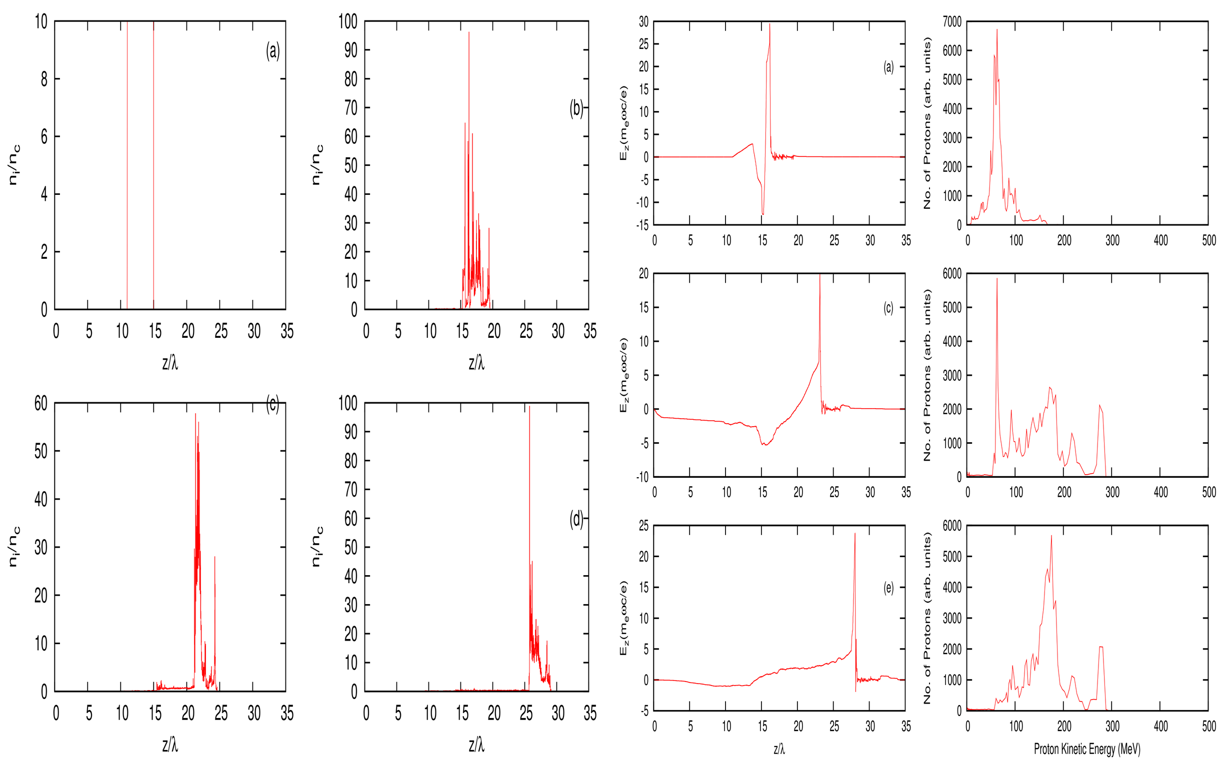
1D3V PIC Simulation Parameters

- Polarization: Circularly Polarized
- Pulse Length: $100t/\tau$ (τ is the time of one laser cycle)
- Dimensionless amplitude (a_0): 20, 30
- Target Thickness: 4λ (λ is the laser wavelength)
- Particles per cell: 100
- Cells per wavelength: 200

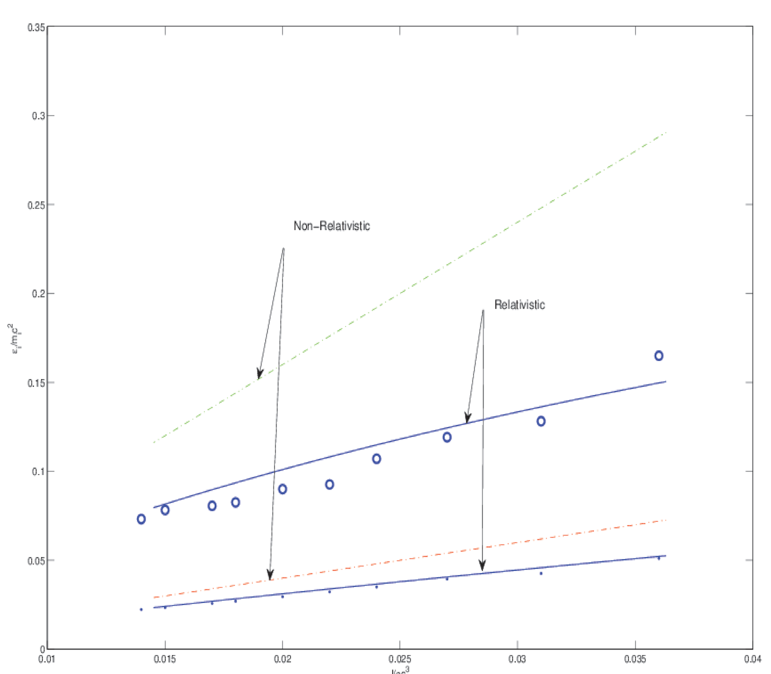
1D3V PIC Simulation Results



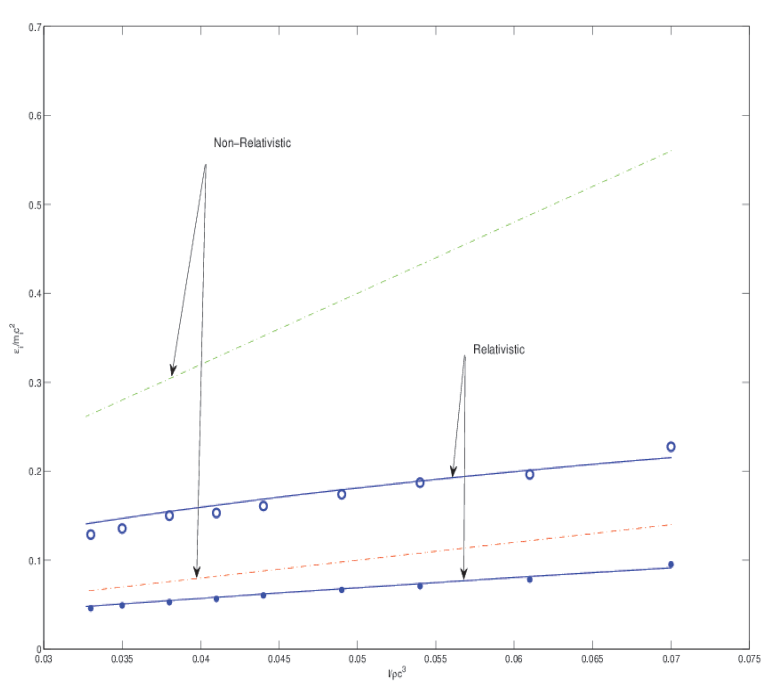
Spatial proton density profile, longitudinal electric field profile and proton energy spectrum at different times for $n_i = 10n_c$ and $a_0 = 20$.



Spatial proton density profile, longitudinal electric field profile and proton energy spectrum at different times for $n_i = 10n_c$ and $a_0 = 30$.



Plots of 1st and 2nd stage ion kinetic energy of accelerated ions for $a_0 = 20$. The analytical results are represented by solid lines and the dots and circles represent first and second stage velocities respectively. The broken lines are the non-relativistic results.

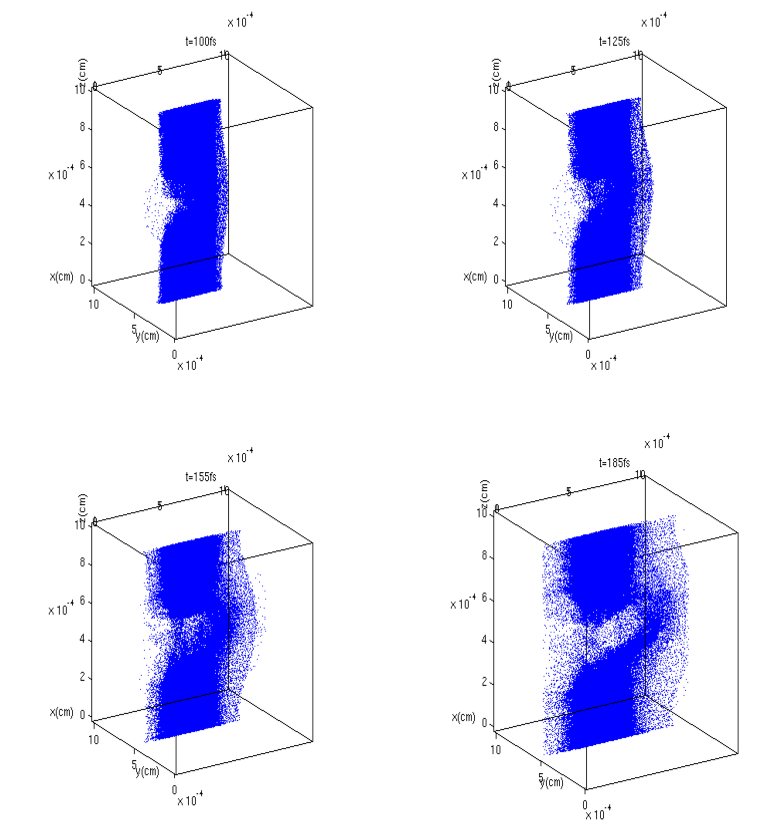


Plots of 1st and 2nd stage ion kinetic energy of accelerated ions for $a_0 = 30$. The analytical results are represented by solid lines and the dots and circles represent first and second stage velocities respectively. The broken lines are the non-relativistic results.

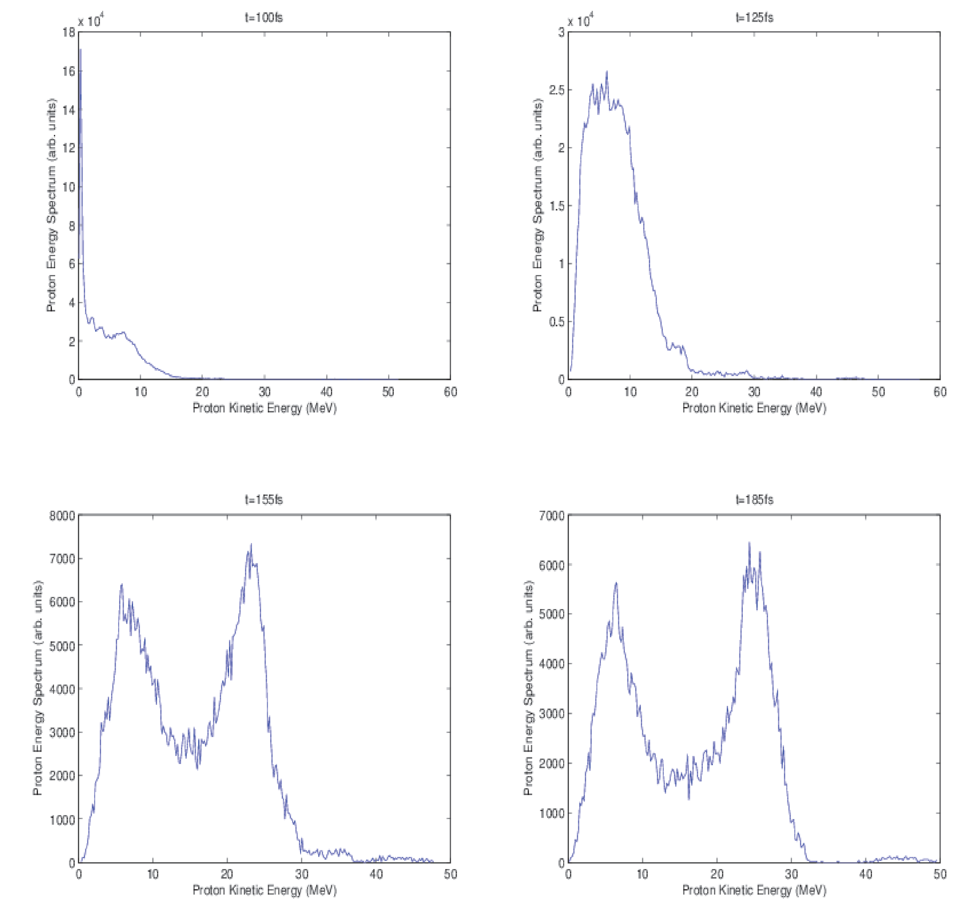
3D PIC Simulation Parameters

- Simulation Box: $10\mu m \times 10\mu m \times 10\mu m$
- Plasma Dimension: $10\mu m \times 10\mu m \times 4\mu m$
- Plasma Density: $1.34 \times 10^{22} cm^{-3}$
- No. of Cells: $250 \times 250 \times 250$
- Particles per cell: 16
- Laser Intensity: $1.37 \times 10^{20} W/cm^2$
- FWHM: $3\mu m$

3D PIC Simulation Results



Ion distribution of the centeral slice of target plasma at different times.



Filtered proton power spectra at different time steps.

Conclusions

- Fully relativistic 1D3V PIC simulations for multistage ion acceleration has been done.
- The first and second stage ion velocity and kinetic energy from PIC simulations match nicely with relativistic analytical calculation.
- The time required for all the ions to attain steady state velocity matches with the relativistic analytical calculation.
- The relativistic calculations are important even if the incident electromagnetic field energy density is smaller than the rest mass energy of ions by a very large factor.
- 3D PIC simulations confirm this process.

References

- Xiaomei Zhang, Baifei Shen, Xuemei Li, Zhangying Jin, Fengchao Wang and Meng Wen, Phys. Plasmas 14, 123108 (2007).
- A P L Robinson, P Gibbon, M Zepf, S Kar, R G Evans and C Bellei Plasma Physics and Controlled Fusion 51, 024004 (2009).
- Xiaomei Zhang, Baifei Shen, Xuemei Li, Zzhangying Jin and Fengchao Wang, Phys. Plasmas **14**, 073101 (2007).
- R. Lichters, R. E. W. Pfund, and J. Meyer-Ter-Vehn, LPIC++: A parallel one-dimensional relativistic electromagnetic particle-in-cell-code for simulating laser-plasma-interactions, Report MPQ 225, Max-Planck-Institut for Quantenoptik, Garching, Germany, 1997, the code is available at http://www.lichters.net/download.html.