Particle-in-cell modeling of an electron acceleration with tilted laser pulses

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Introduction

The challenge in using laser pulses to accelerate electrons is the significant difference in velocity between electrons and light waves. For various acceleration methods, such as direct field acceleration, Wakefield acceleration, and ponderomotive acceleration, the relative velocity between the pulse's group velocity and electron velocity is crucial. Typically, both the phase and group velocities are near the speed of light, necessitating the injection of fast electrons synchronized with the pulse. To address this issue, researchers have explored spatio-temporal shaping of laser pulses, using techniques like spatial chirping to manipulate the pulse's group velocity. Angular spatial chirping, in particular, results in a tilted pulse front, that can be used to reduce the effective pulse velocity below the speed of light. Our goal is to do full-field simulations using V-Sim particle-in-cell simulation software, to confirm the theoretical model.

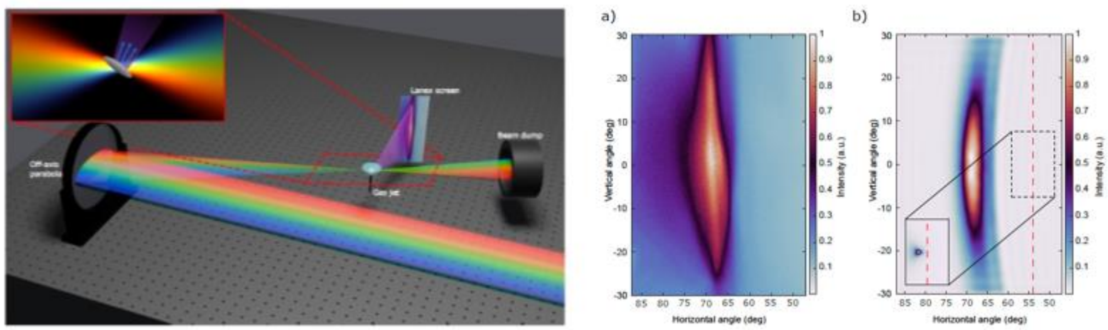
The history of accelerating electrons with laser pulses dates back to early laser physics. In 1963, Gordon and Warren proposed the concept, but it wasn't until the 1990s that it was experimentally realized, thanks to advances in laser tech and simulation software. The method involves angular spatial chirping to create a tilted pulse front, allowing synchronization with electrons. This has led to significant advancements in laser-driven electron acceleration, enabling table-top accelerators producing energies up to hundreds of MeV. Challenges remain in achieving high-energy beams with good energy spread and developing efficient, scalable methods. Our research aims to address these challenges, potentially impacting areas like ultrafast electron diffraction.

Wilhelm and Durfee have proposed a novel scheme for using the ponderomotive force of a tilted ultrafast laser pulse to accelerate electrons in free space [1]. For creating simulation to compare to the analytic model, they used OSIRIS code [2]. OSIRIS is an object-oriented simulation tool that accommodates 1D, 2D, and 3D simulations in various coordinate systems, offering full relativistic capabilities, charge-conserving current deposition, and adaptability for diverse research problems. The research findings using PIC modeling in plasma-based accelerators include the investigation of a particle injection scheme, the discovery of a long-wavelength hosing instability in long laser pulses, the successful utilization of a parabolic plasma channel to prevent laser pulse diffraction in Laser Wakefield Accelerators (LWFA), and insights into Plasma Wakefield Accelerators (PWFA) in the blowout regime [2]. These results emphasize the significance of PIC modeling and OSIRIS in advancing the understanding and application of plasma-based accelerator technology. However, 3D simulations of LWFA are resource-intensive but offer a more detailed understanding of the entire system. For PWFA in the blowout regime, exploring the significance of tail hosing instability requires 3D simulations over extended distances. A crucial challenge for this code is simulating accelerators over their full acceleration distance, necessitating efficient use of computational resources through mechanisms like dynamic load balancing, adaptive mesh refinement, and advanced boundary conditions. In addition, this model did not include Coulomb forces between the particles. Using V-SIM we will have more efficient use of computational power and will also be more accurate as it will take into account the Coulomb forces between the particles.

Another research [3] examines how intense lasers can rapidly accelerate electrons to high energies, relevant for fast ignition, high-energy physics, radiography, and secondary particle sources. It focuses on Vacuum Laser Acceleration (VLA), which offers simplicity and high acceleration gradients but faces challenges in effectively injecting electrons into the laser field. The research introduces a new VLA approach using the relativistic transparency effect. When a high-contrast laser interacts with a thin solid foil, electrons are accelerated and injected into the transmitted laser field as the plasma becomes relativistically transparent, resulting in the generation of high-energy electrons up to 20 MeV. This sheds light on electron dynamics in relativistic transparency plasmas and has implications for laser ion accelerators and secondary sources. The method works by mitigating the barrier effect that prevents electrons from entering the transmitted laser field, enabling phase-stable VLA until they scatter radially.

I use both analysis and experiments to verify simulation results. This study [4] is one such verification. The figures below illustrate the experimental setup and results of electron acceleration from study [4], using direct ponderomotive acceleration with 1.5J tilted ultrafast pulses. Electrons below 500keV are propelled perpendicular to the tilted pulse front. Figure below shows setup and results.

Experimental demonstration of electron acceleration using tilted ultrafast pulses



Schematic of experimental configuration.

(a) Measured electron beam on Lanex scintillator screen. (b) calculated distribution using simplified single-particle model.

Figure 1: showing experimental setup and results of accelerating electrons with tilted ultrafast pulses.

<u>Procedures</u>

The V-Sim Particle-in-Cell (PIC) code operates entirely in the time-domain and only comes with plane-wave and Gaussian beam inputs. To launch an arbitrary field into the domain, we must fully specify the E-field at the left boundary.

In the spatial and spectral domain, we start with a pulse that has transverse chirp. We then take the spatial Fourier transform to calculate the field at focus. Then propagate the beam from there and finally calculate the inverse Fourier transform to get back in time domain. This way we get full 3D equation for E-field.

First, for simple 2D gaussian beams, I measured if the simulated beam width changes over time followed the expected theoretical equation to make sure simulation is indeed working as expected. Next, I took a full 3D complex tilted beam equation that we got earlier and converted it into 2D. Since simulation only takes the real equation, I also took its real part to put into the simulation. Then, I propagated this 2D tilted gaussian beam in x, while polarized in y or z (tested both), with the tilt of 60° in xy-plane and spot size of 30microns with 800nm wavelength. To make sure all my functions worked properly, I also coded the same functions in python and verified that each function behaved as expected. This solution is a viable option since V-Sim has enough computational power to do the simulation. It has been used in similar simulations before, and we also verified all our results analytically or by comparing them to existing models to make sure the software is accurate in its calculations.

<u>Results to Date</u>

The 2D simulation of tilted gaussian beam propagation is working as expected. The final real equation for the spatio-temporal field in 3D is:

$$E = \sqrt{\frac{4\,\mathcal{E}_0}{\sqrt{\frac{\pi}{2}}\;\mathrm{w0}^2\,\Delta\omega}}\;\frac{w_0}{w_L}\;\mathrm{Exp}\!\left[-\frac{x^2}{{w_L}^2\,{\beta_{\mathrm{BAL}}}^2}-\frac{y^2}{{w_L}^2}\right]\frac{e^{i\left(\varphi0\mathrm{Loc}-\frac{\Delta\omega\mathrm{Loc}^2\,(t-\varphi1\mathrm{Loc})^2}{4\,i+4\,\Delta\omega\mathrm{Loc}^2\,\varphi2\mathrm{Loc}}\right)}}{2\sqrt{\pi}\;\sqrt{\frac{1}{\Delta\omega\mathrm{Loc}^2}-i\,\varphi2\mathrm{Loc}}}$$

Note that except for w0, Δw, π and ε0, rest of the parameters of the function are also auxiliary functions themselves. We are using the real part of the 2D version of this function for simulation. We get a 2D version by replacing y with 0, x with y, and z with x in this order.

Initially I was using the regular gaussian beam with no tilt to learn how the simulation worked and to verify if simulation gave correct results for simpler cases. I wanted to verify if the beam width evolved according to the known analytical function. In this process I discovered that since the simulation included the carrier frequency, width measurements were difficult. I made a function to use the FFT to remove the carrier. With this I verified that simulation was following closely to theoretical model. From the 2 plots below, the left one shows what was seen on simulation plotting tool, and the right one is the result of our FFT.

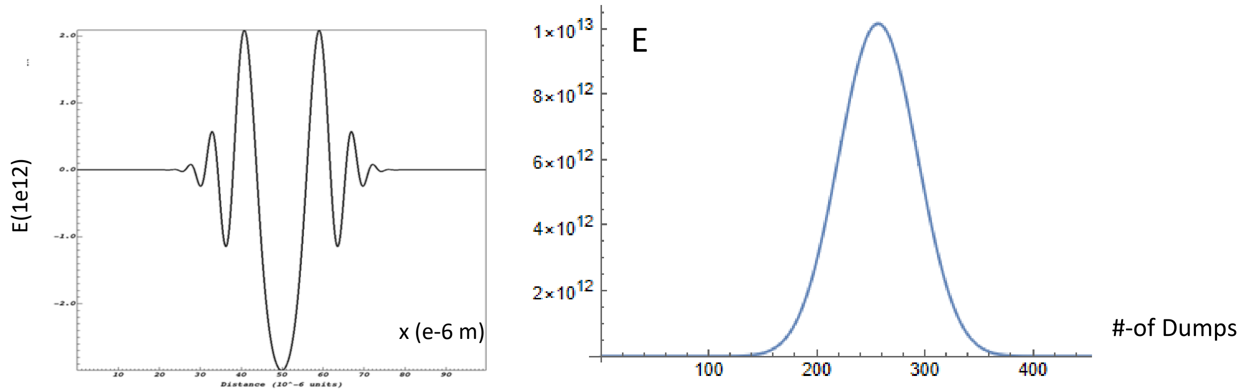
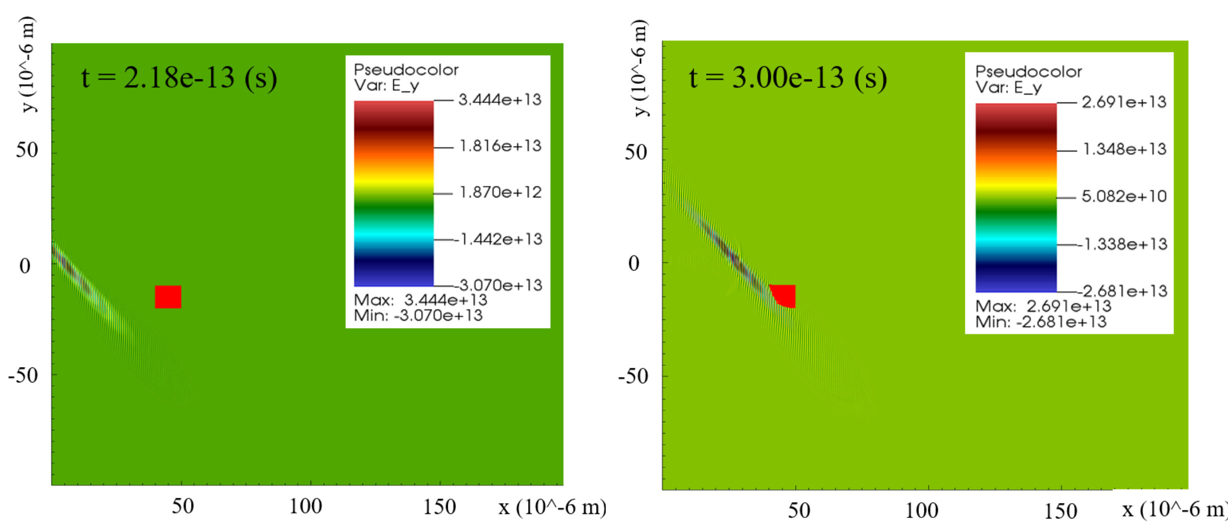


Figure 2: 2D simulation of simple gaussian beam propagation, extra noise is visible. Where x = C*T #DumpRate * #-of Dumps, where C is speed of light (3*10^8 m/s), T is time step, which for this sample simulation was set to 1.092E-16 (s). #DumpRate was also set to 250, with total of 4000 steps, so for each time slice #-of Dumps depends on which period we are looking at. Y-axis is E-field (V/m).

With tilted beam equation, from the left boundary, we launched the beam with spot size of 30microns with 800nm wavelength and 60° tilt that propagates in x direction, polarized in y direction. As expected, we see E_x and E_y components, and E_z = 0. Plots below show E_y as it propagates. We first observe that pulse is coming in from outside grid, then it hits electrons and accelerates them. Some of them 'ride' the wave, and some get left behind. The shape of the pulse also follows the theoretical model as it has one end wider, another end narrower. It is centered at y = 0, so intensity is lower farther away from center peak. We also tested using different inputs for spot size, wavelength, field strength and more to make sure results were consistent. We also found that it was threshold E-field strength of order of 10^13 that accelerated electrons. Magnitudes of 10^12 or less would just pass through the electrons. The electron density I used was on the order of 10^19 electrons per square meter.



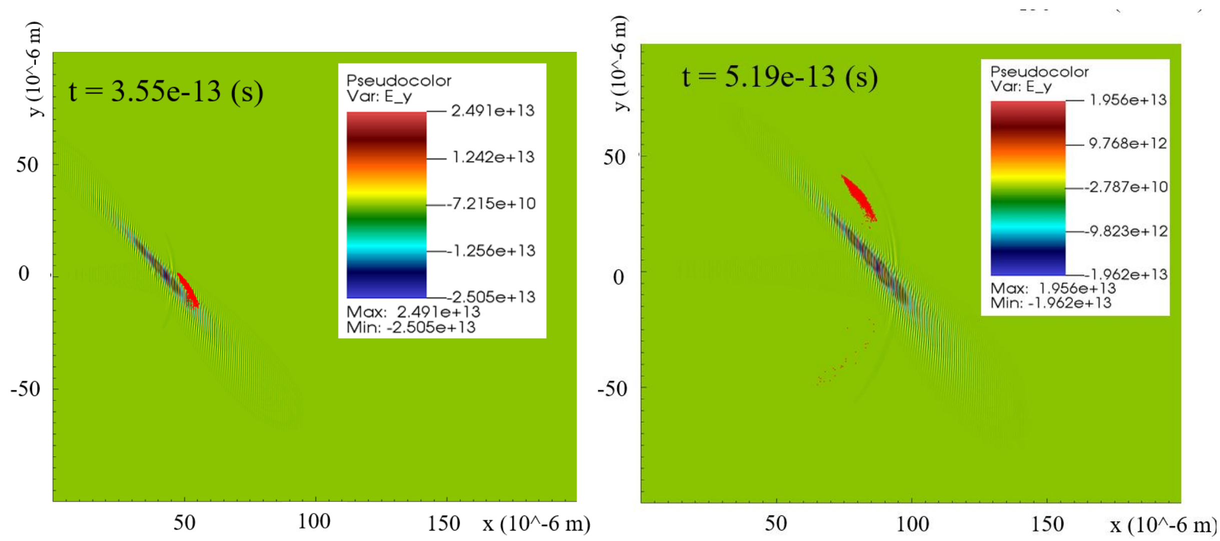


Figure 3: Using full 2D titled beam equation to propagate the beam. Plots show the time evolution as a beam hits electrons and accelerates them. The small graph on the plot shows field strength color coded. x and y axis are grid dimensions in meters. Red dots are electrons.

I also did simulation with same inputs, but polarized in z. The result was that I only saw E-field in z-direction, while E_x and E_y components of field were practically zero. Again, this result was consistent with the analytical models.

For the example with y polarization, we expected to see E_x and E_y and we did, but we never gave simulation the E_x. We need to verify that E_x, that software added through solving maxwell's equations, is what it should be. Next step would be simulating this in 3D and adding ions as well, but it might require access to supercomputer due to high computational requirements.

Statement of Work

Tasks

Using V-Sim PIC simulation software, simulate the use of tilted laser beam to accelerate electrons in a vacuum. Subsequently, I will perform a comparative analysis between the simulated beam propagation and theoretical analytic models. To systematically progress through this research, I will initially undertake simulations involving a straightforward 2D Gaussian beam with no tilt, cross-referencing the results with the corresponding mathematical model to verify their concordance. Subsequently, I will introduce a more comprehensive equation for the beam, incorporating the tilt. Throughout the simulation process, I will employ Python and Mathematica for data analysis, enabling a comprehensive exploration of field dynamics and providing a visual representation of the simulation outcomes.

Deliverables

I will deliver a Python code, used by the V-Sim to set up simulation, which correctly simulates the use of tilted laser beam to accelerate electrons in a vacuum that agrees with the analytical model. I will also deliver python and Mathematica codes used for analysis/verification.

Timeline

The incremental steps are planned to be executed over a 24-week timeframe, with a broader project timeline detailed in Table 1 below.

Table 1: Timeline for Mines Particle-in-cell modeling over the course of 10/24/2023-04/30/2024

Task	Weeks (1-4)	Weeks (5-8)	Weeks (9-12)	Weeks (13-16)	Weeks (17-20)	Weeks (21-24)
2D model no tilt	X X X X	X X				
Get Full 2D into Vsim		X X	X X			
Verify through python			X X	X X X X	X	
Full 2D Model with tilt					X X X	X X
Final verification						X X

<u>Cost Analysis</u>

There are few costs to this project. Equipment is the Linux server at Mines with 128GB RAM and AMD CPU, which was already in use before this project, so its cost is excluded here. Main source of cost is the yearly subscription to Tech-X's V-Sim software. Other than that, student labor is the only source of cost.

Table 2: Cost Analysis for Mines Particle-in-cell modeling simulations

Item	Unit Cost	Quantity	Unit	Cost	Comments
V-Sim Subscription	$5,000	1	Yearly	$5,000	Consumables
Labor - 1 Student	$20.00	200	hr	$4,000	Labor Cost
Overhead = 50% of Labor	-	-	-	$2,000	Overhead Costs
			TOTAL COSTS	**$11,000**	

Some of the available resources are getting consultation from an expert working for the Tech-X company that owns the simulation V-Sim. If needed, memory (RAM) can be increased on the server to allow for more complex simulations to run.

References

1. Wilhelm Alex, Durfee Charles. Tilted Snowplow Ponderomotive Electron Acceleration With Spatio-Temporally Shaped Ultrafast Laser Pulses. Frontiers in Physics. 7. 10.3389/fphy.2019.00066. (2019).

2. Hemker RG. Particle-in-cell modeling of plasma-based accelerators in two and three dimensions. arXivorg. (2015).

3. Singh, P.K., Li, FY., Huang, CK. *et al.* Vacuum laser acceleration of super-ponderomotive electrons using relativistic transparency injection. *Nat Commun* **13**, 54 (2022).

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