Simulating Accelerating Electrons with Tilted Gaussian Beam

Zakaria Khitirishvili, David Flammer, Charles Durfee

Dept of Physics, Colorado School of Mines, Golden, CO 80401

NSF/DOE Basic Plasma Science and Engineering

Abstract

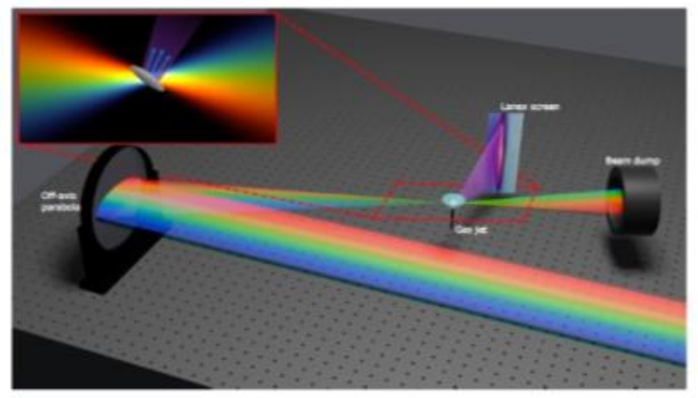
The ponderomotive force is the force experienced by charged particles in the presence of a rapidly oscillating electromagnetic field, such as a laser beam, causing them to be pushed in the direction of the field's intensity gradient.

Using ponderomotive force of a tilted Gaussian beam, we can accelerate electrons in free space. The tilt of the intensity profile comes from the angular dispersion of the pulse's spectrum and increases the interaction time of the pulse with the free electrons. Using Tech-X VSim software we aim to simulate the acceleration of electrons in free space and find the threshold amplitude of E-field

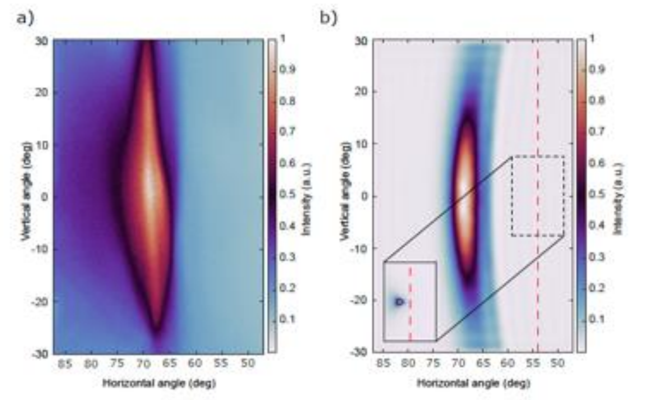
Experimental Setup and Results

We rely on both analytical and experimental results to cross check the simulation results. Figures below show the schematic of experiment setup, as well as its results for electron acceleration.

Experimental demonstration of electron acceleration using tilted ultrafast pulses [1]



Schematic of experimental configuration.

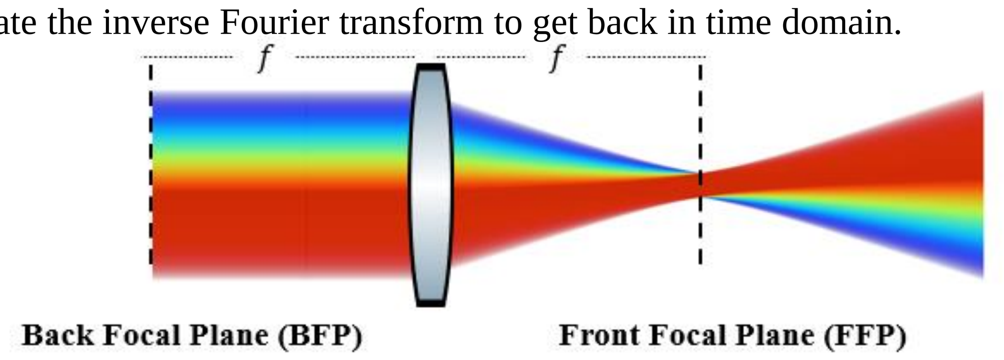


(a) Measured electron beam on Lanex scintillator screen. (b) calculated distribution using simplified single-particle model.

Analytical Calculation of the Time-Domain Field

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.



1. Input field at back focal plane: $E(x,y) = e^{-\left((x-\alpha\,\delta\omega)^2+y^2\right)/w_{in}^2}\; e^{-\delta\omega^2/\Delta\omega^2}$
2. Field at front focal plane: $E(X,Y) = \mathcal{F}\{E(x,y)\} \approx e^{-\frac{(ct-x\tan\theta_{pf}-z)^2}{c^2\tau^2}}\, e^{-(x^2+y^2)/w_0^2}$
3. Fresnel propagate away from focus
4. Expand spectral phase around local central frequency to second order
5. Inverse Fourier transform to the time domain

Implementing the E-field Equation into V-Sim

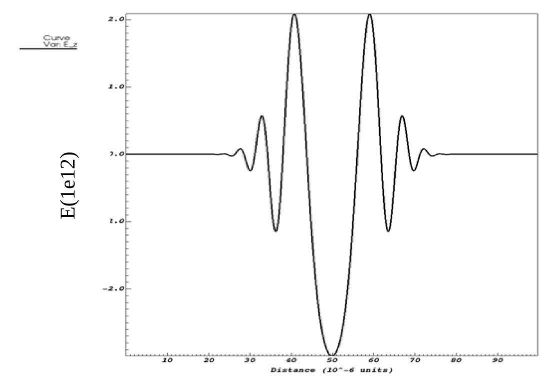
The final equation for the spatio-temporal field in 3D is:

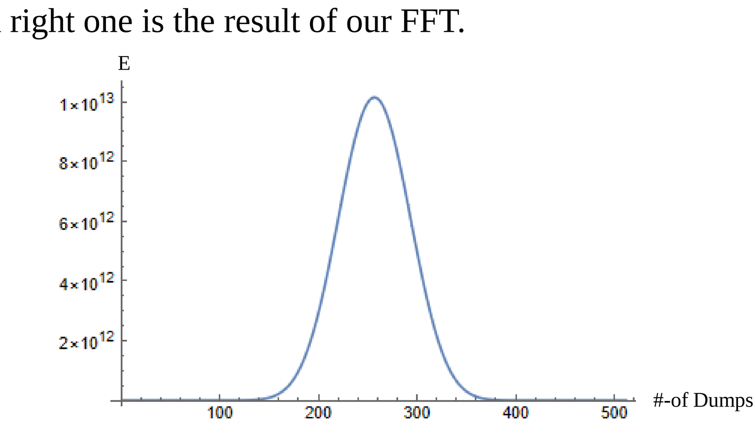
$$E = \sqrt{\frac{4\,\mathcal{E}_0}{\sqrt{\frac{\pi}{2}}\,\mathrm{w0}^2\,\Delta\omega}}\;\frac{w_0}{w_L}\,\mathrm{Exp}\left[-\frac{x^2}{{w_L}^2\,{\beta_{\mathrm{BAL}}}^2}-\frac{y^2}{{w_L}^2}\right]\frac{e^{i\left(\varphi0\mathrm{Loc}-\frac{\Delta\omega\mathrm{Loc}^2\,(t-\varphi1\mathrm{Loc})^2}{4\,i+4\,\Delta\omega\mathrm{Loc}^2\,\varphi2\mathrm{Loc}}\right)}}{2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

- Note that most parameters of the function are also functions themselves
- Use real part and 2D version of the full E-field equation for the simulation
- To convert expression into VSim code:
    1. Take the real part of the original equation
    2. Convert to 2D version (replace y with 0, x with y, z with x)
    3. Convert the expression to python function and verify
    4. Convert python function to VSim code (very similar to python)
    5. Do same for all auxiliary functions

Verifying for simple cases

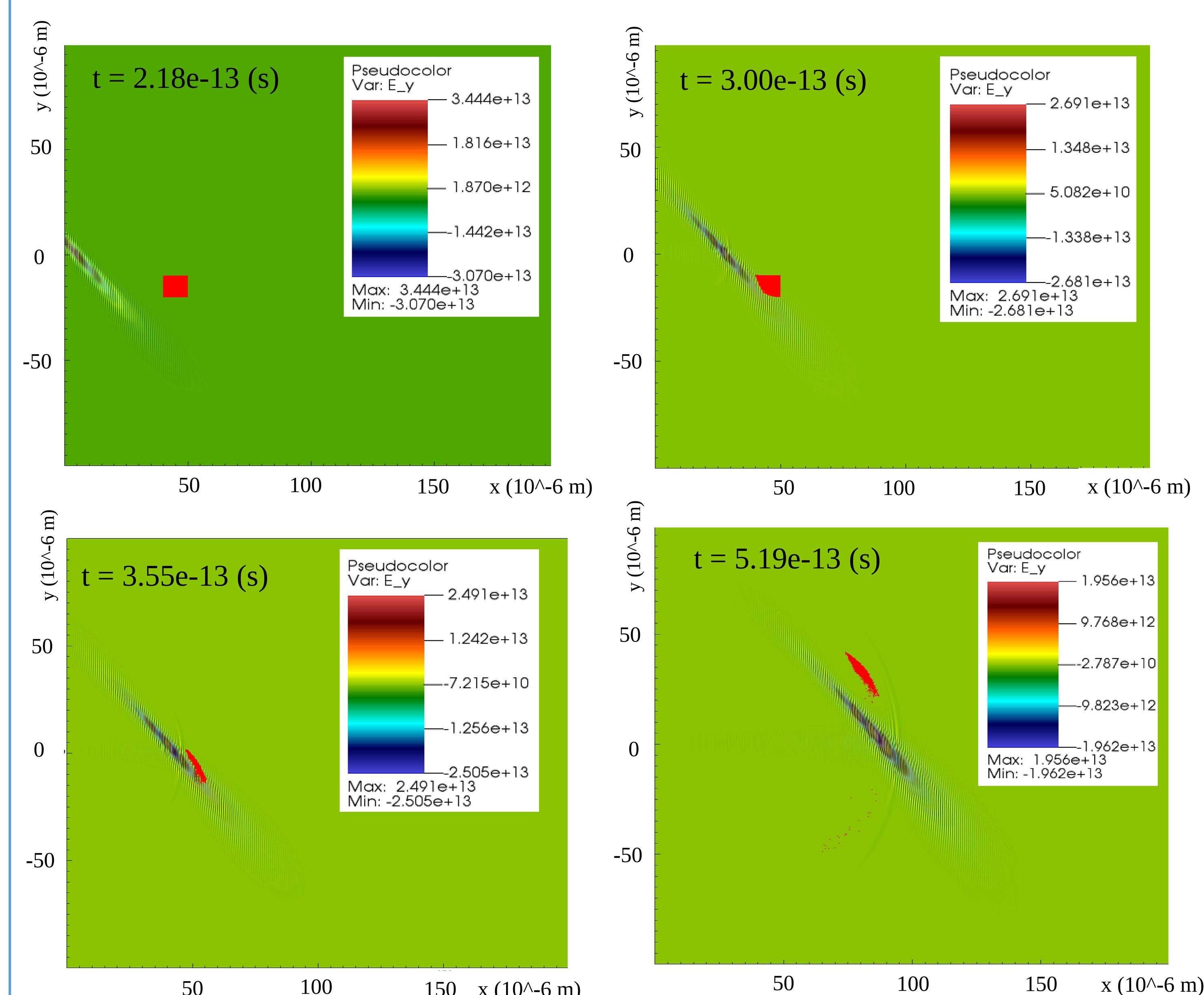
Initially we were using the regular gaussian beam with no tilt to learn how the simulation worked and to verify if simulation gave correct results for simpler cases. We wanted to verify if the beam width evolved according to the known analytical function. In this process we discovered that since the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





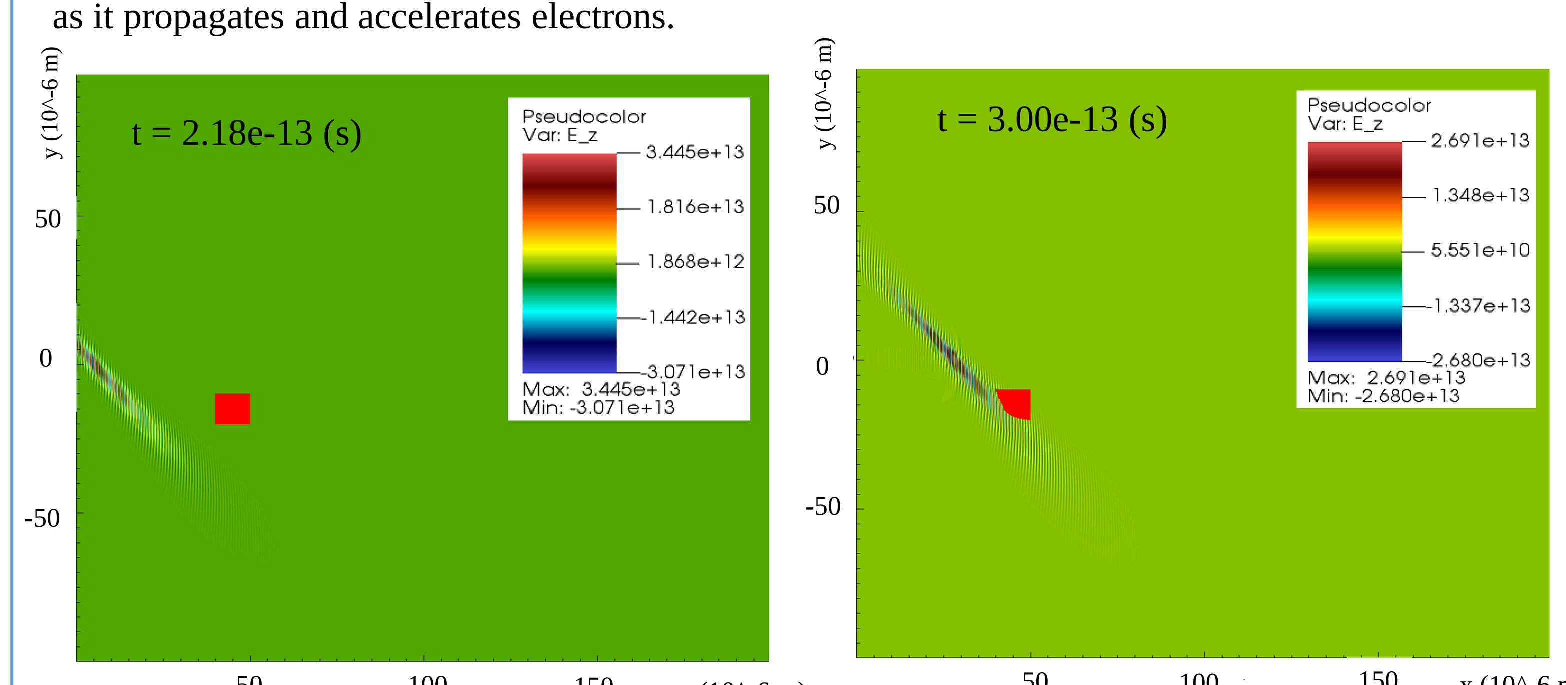
Propagating in X, Polarized in Y

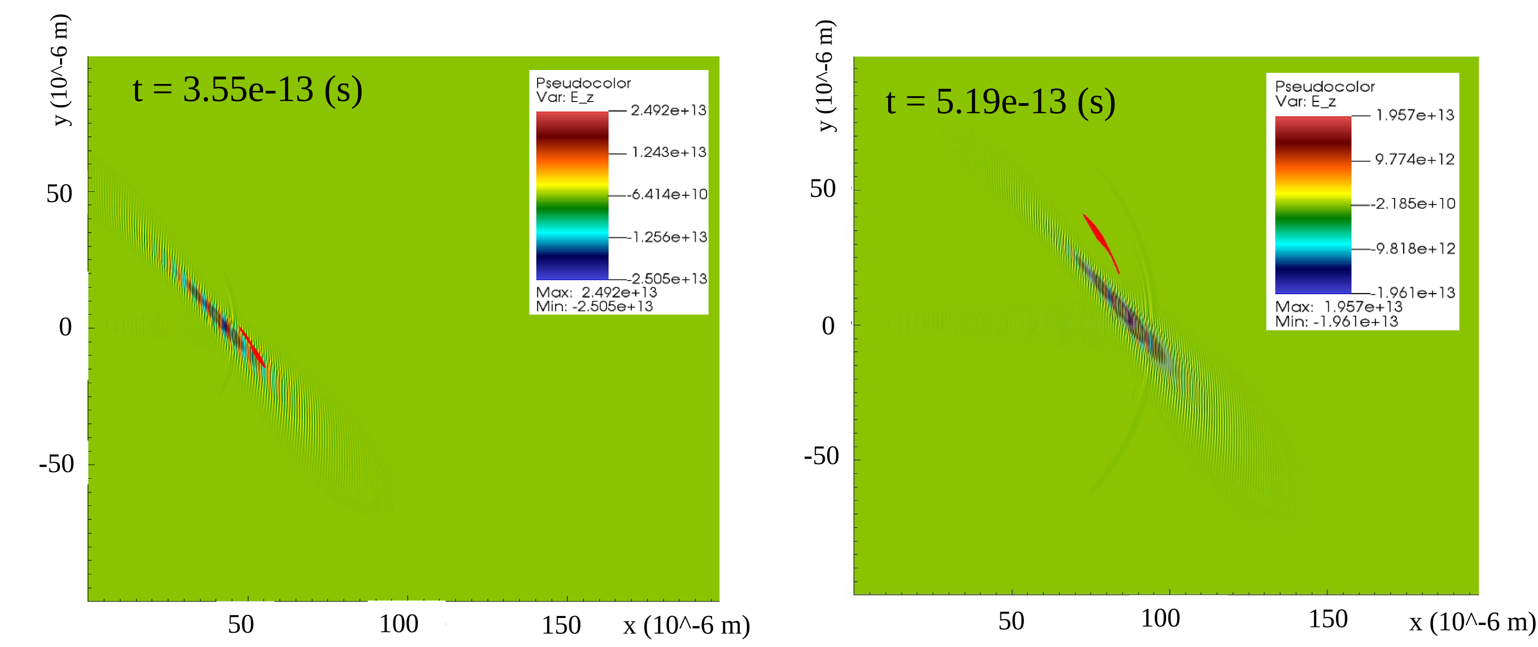
From left boundary, we launched the beam with spot size of 30microns with 800nm wavelength and 60° tilt that propagates in x direction, polarized in y direction. As expected, we see E_x and E_y, and E_z = 0. Plots below show E_y as it propagates. We first observe that pulse is coming in from ourside grid, then it hits electrons and accelerates them. Some of them 'ride' the wave, and some get left behind.



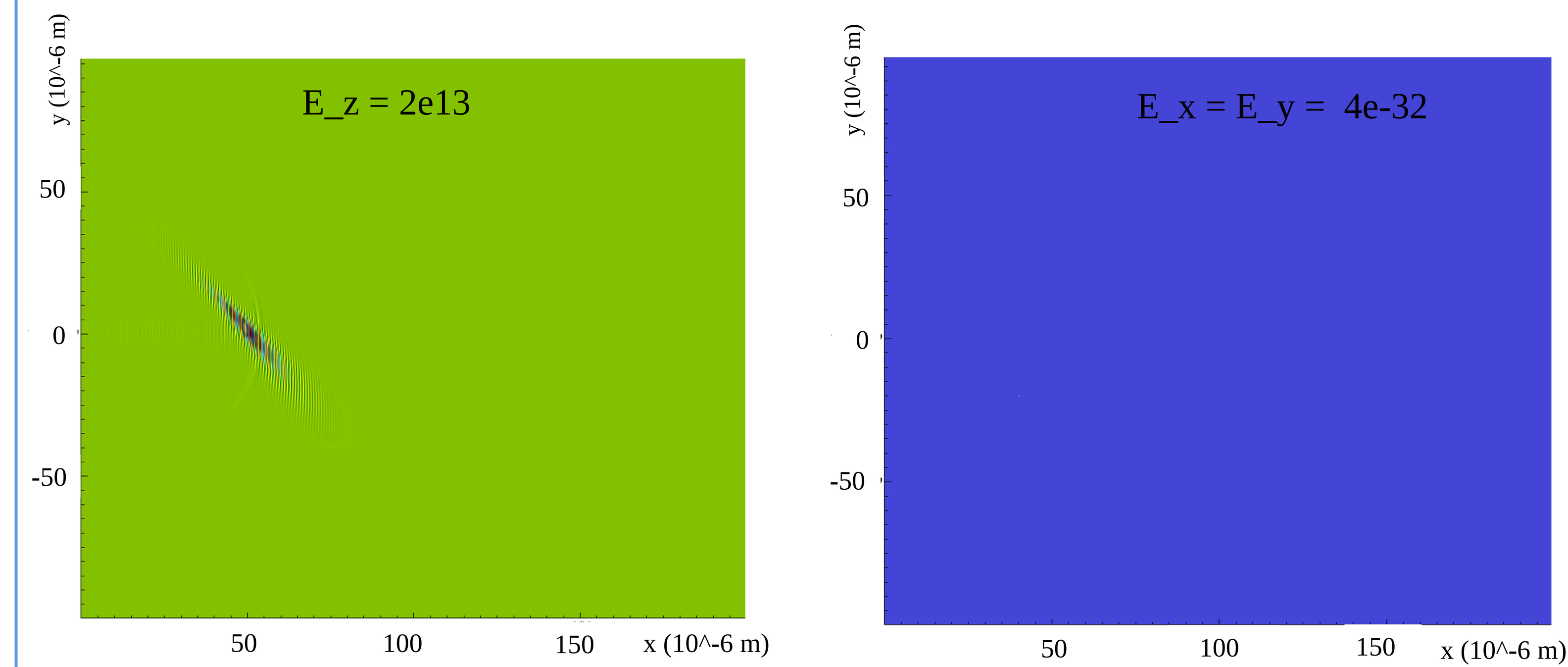
Propagating in X, Polarized in Z

Using same parameters as before, we only changed the polarization to z direction. Here we only expected to see E_z, and other components should be zero. Plot below shows E_z at different times as it propagates and accelerates electrons.





Figures below show that as expected, for beam propagating in +x, polarized in z, we only see E-field in z-direction(left plot), while in x and y it's practically zero(right plot). Similarly, when polarized in y, field in z is 0 and we have some field in x and y. These results agree with the analytical models.



Conclusions and Future Work

We successfully simulated the ponderomotive acceleration of electrons in 2D and found the approximate threshold amplitude of E-field. We showed that for different polarizations, simulation gives fields that follow the analytical model. However, for the example with y polarization, we expected to see E_x and E_y, 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.

References

[1] "Ponderomotive snowplow electron acceleration with high energy tilted ultrafast laser pulses," P. Hunt, A. Wilhelm, D. Adams, S. Wang, R. Hollinger, Z. Shpilman, S. Anaraki, N. Westlake, D. Schmidt, J. Rocca, C. Durfee, *under review*, Nature Communications (2024).

Acknowledgments

Special thanks to project mentors Charles Durfee and David Flammer for helping me work through this project.

Project Design Requirements

#	Requirements	Verification Method	Verified (Yes or No)	Application	Description
1	Propagate Gaussian Beam through V-Sim.	Compare to analytic functions	Yes	Code verification	Using simple beam, verify that beam width is changing as expected
2	Code E-filed equation in python to make sure input functions are correct	Compare to analytic functions	Yes	Code verification	Verify all auxiliary functions work well before putting everything together
3	Learn how to launch arbitrary EM wave from entry boundary of the grid.	Demonstration	Yes	Can be used to accelerate electrons	This will be useful with any field to learn how launchers work in simulation.
4	Add electrons and demonstrate acceleration looks physically reasonable	Demonstration And analytical	yes	This can be used in any application that requires adding in e with some energy	Some electrons should follow wave closely, others might go along nearby.