Nuclear Science & Security Consortium

Simulations in Laser Wakefield Acceleration

Exploring the parameters that control injection in multiple buckets

Camille Woicekowski - University of California, Berkeley

Abstract

Laser-plasma acceleration is an emerging technology capable of creating compact, affordable accelerators in the near future. This has exciting applications in high-energy particle colliders, medical treatment, and national security. For acceleration to occur, electrons must be injected into the wakefield of the laser. How and where injection occurs is important in determining the final properties of accelerated particles. However, the current theory of injection does not always match experimental observations. This research explores potential causes for the gap between theory and observation. Simulations were run using particle-in-cell code WarpX to explore how different parameters affect electron injection. A strong relationship between the intensity of the laser and position of injection was found. This effect may be a result of beamloading; a phenomena that occurs when the injected charge is large enough to drive a wakefield of its own behind the laser.

Background

Laser-plasma acceleration, or laser wakefield acceleration, is a developing technology for accelerating electrons. The phenomena occurs when an ultra-short, high-intensity laser pulse is focused into a gas jet. The laser creates a strong electric and magnetic field in its wake and ionizes the gas into a plasma, generating a powerful accelerating structure. The structure is capable of accelerating particles to multi-GeV energies within only tens of centimeters acceleration distance. Compared with conventional methods that require structures kilometers long to achieve similar energies, laser plasma accelerators (LPAs) offer exciting prospects for developing compact, inexpensive accelerators.

High energy electron accelerators can be used to probe for concealed nuclear material. Creating a compact, portable LPA has promising applications for nuclear nonproliferation and national security in the near future.

The positively charged ions within the plasma are several orders of magnitude larger and heavier than the electrons. As a result, ions are essentially motionless on timescales of interest, while electrons experience a repelling force from the high-intensity laser (*ponderomotive* force). The electrons separate spatially from the ions, resulting in the charge separation depicted in the figure below. The ion cavities represented by the dark blue shades are commonly referred to as *buckets*.

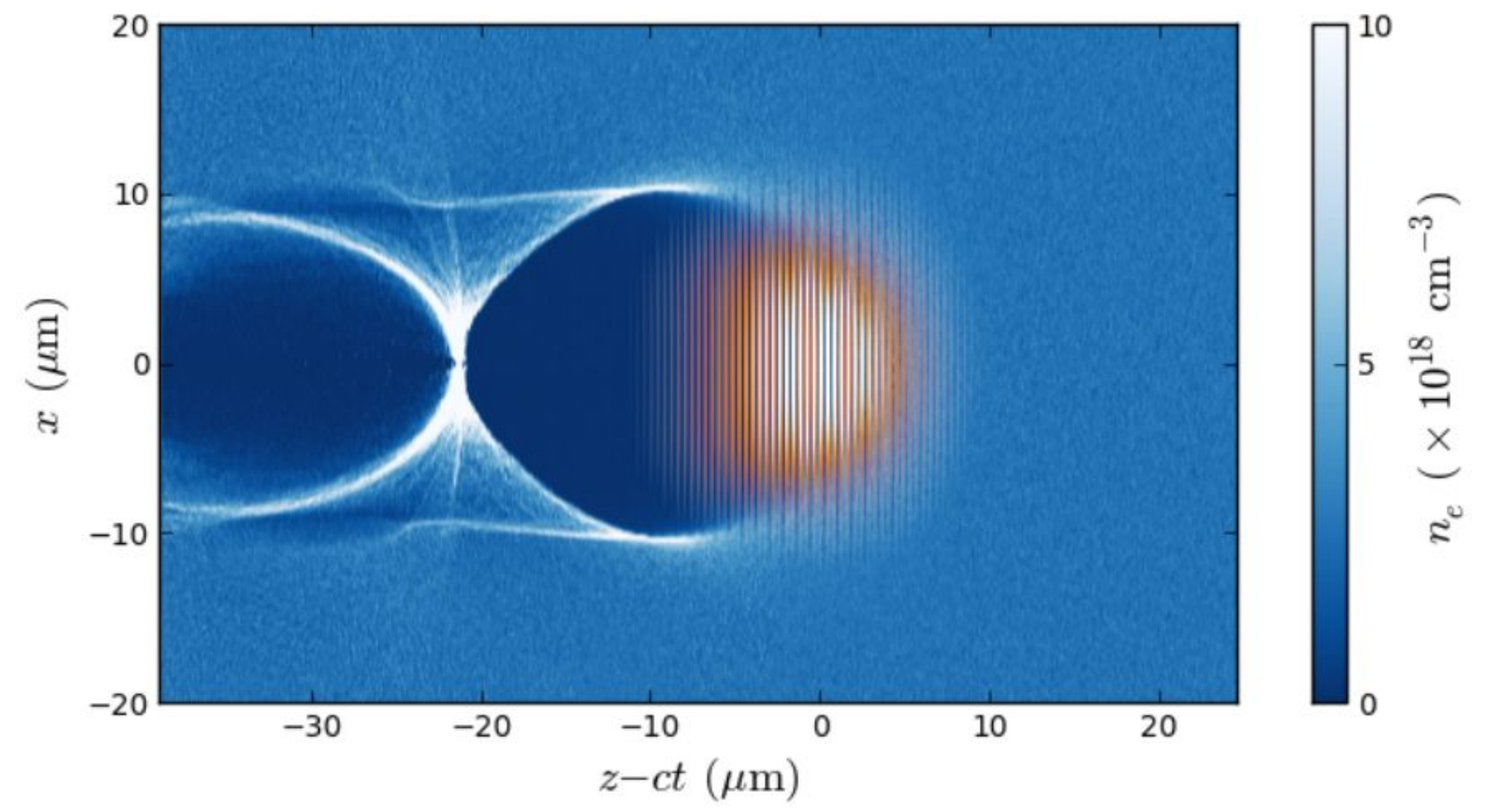

Figure 1. The red and yellow represent the laser pulse while blue tones show the electron density

The laser and its wake propagate with velocities near the speed of light. A resting particle that enters the wakefield would slip between buckets, experiencing successive accelerating and decelerating forces and resulting in no net energy gain. Thus, for an electron to be accelerated within the plasma, it must enter with an already relativistic velocity. *Injection* is the process by which a portion of the plasma electrons are placed inside the ion cavity with sufficient initial speed to remain within the accelerating region. The injection process largely determines important qualities of the accelerated electrons (or the *bunch*), such as their final energy and energy spread.

Introduction

Density downramp injection is a method through which electrons are captured in the accelerating region by controllably expanding the ion cavity. To trigger this process, a spike is created in the the density of the gas jet, followed by a downramp. The size of the bucket is inversely proportional to the density of the gas, so the ion cavity expands as the laser propagates into lower density. This expansion captures relativistic plasma electrons, thereby triggering injection.

Downramp injection theory (Esarey, R.M.P., 2009) predicts that injection occurs when the velocity of the plasma electrons exceeds the velocity of the back of the bucket. The velocity of the buckets decreases with distance behind the driver. Therefore, this theory predicts that later buckets (i.e., buckets further behind the driving laser) must have a higher injected charge. Recent experiments in downramp injection (Tsai, Physics of Plasmas, 2018), however, have shown injection to occur only in the first bucket. What accounts for this apparent paradox between theory and observation?

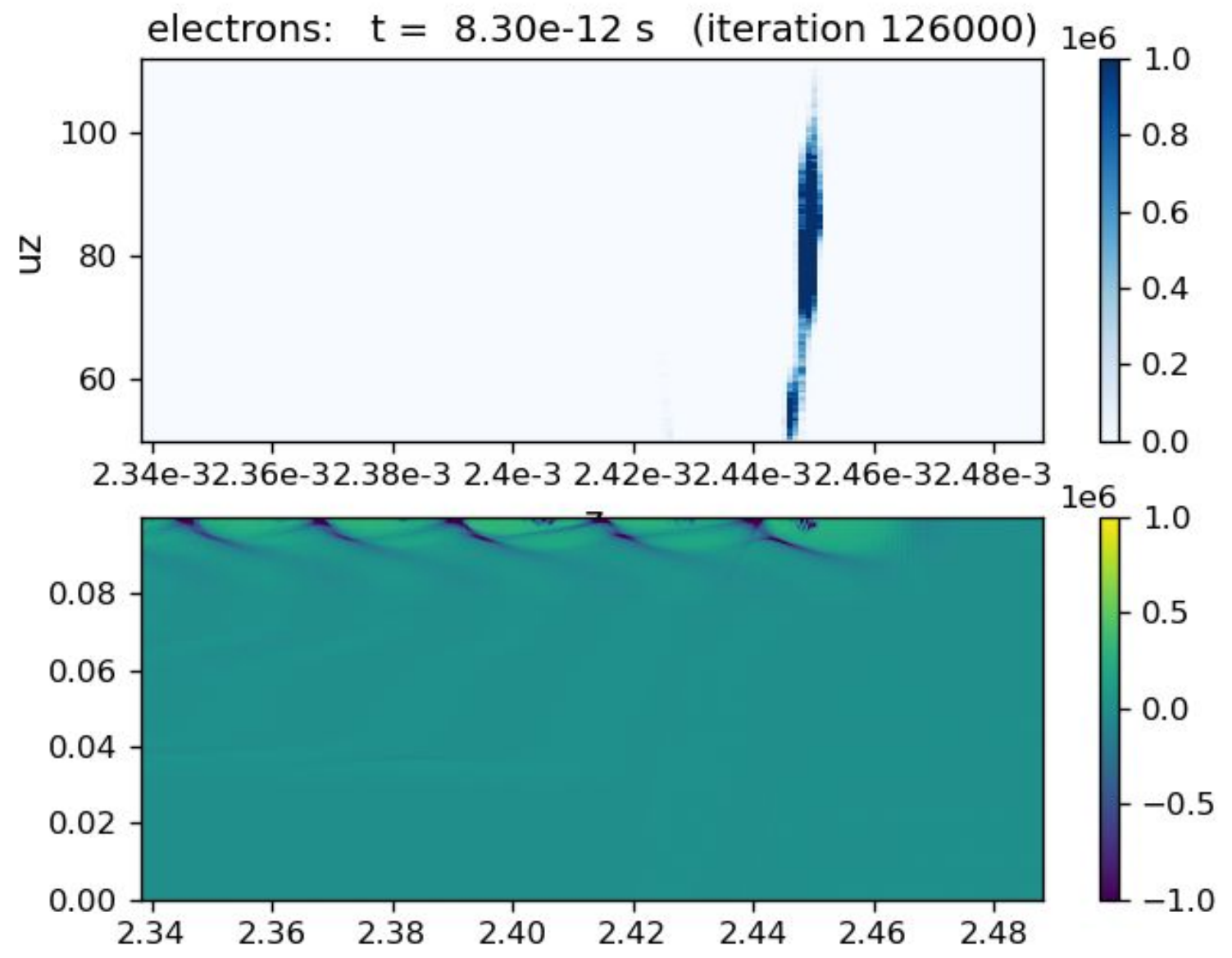

Figure 2. Top plot shows the velocity of the injected electrons, while the bottom plot shows charge density of the wakefield. Here, we see injection in the first bucket only.

Methods

Multi-GPU simulations were run using WarpX on Perlmutter through National Energy Research Scientific Computing Center (NERSC). WarpX is an open-source, particle-in-cell (PIC) code with advanced algorithms for plasma acceleration. The PIC technique is designed to capture dynamics of plasma through solving Maxwells equations on a grid and simultaneously solving the equations of motion for the plasma using macroparticles. This method allows for accurate modeling of wake formation and electron trapping and acceleration over a wide range of spatial and temporal scales.

Post-processing scripts were created using NERSC JupyterHub to extract relevant information from simulation data. In particular, this research focused on the effects of the gas density spike and laser intensity on injection.

References

Esarey, E., Schroeder, C. B., and Leemans, W. P. (2009). Physics of laser-driven plasma-based electron accelerators. Rev. Mod. Phys., 81:1229–1285.

Katsouleas, T., Wilks, S., Chen, P., Dawson, J. M., and Su, J. J. (1987). Beam loading in plasma accelerators. Particle Accelerators, 22:81–99

R. Lehe. Improvement of laser-wakefield accelerators: towards a compact free electron laser. Plasma Physics. Ecole Polytechnique, 2014. English.

Tsai, H., Swanson, K.K., Barber, S.K., et al. (2018). Control of quasi-monoenergetic electron beams from laser-plasma accelerators with adjustable shock density profile. Physics of Plasmas 25(4), 043107-043107.

Results

Simulation results show that amount of charge injected into each bucket is strongly dependent on the intensity (a0) of the driving laser. In the regime where a0 is low, the results agree with injection theory: injection predominantly occurs in later buckets. In the high intensity regime, simulations match recent experiments: electrons are injected primarily into the first bucket.

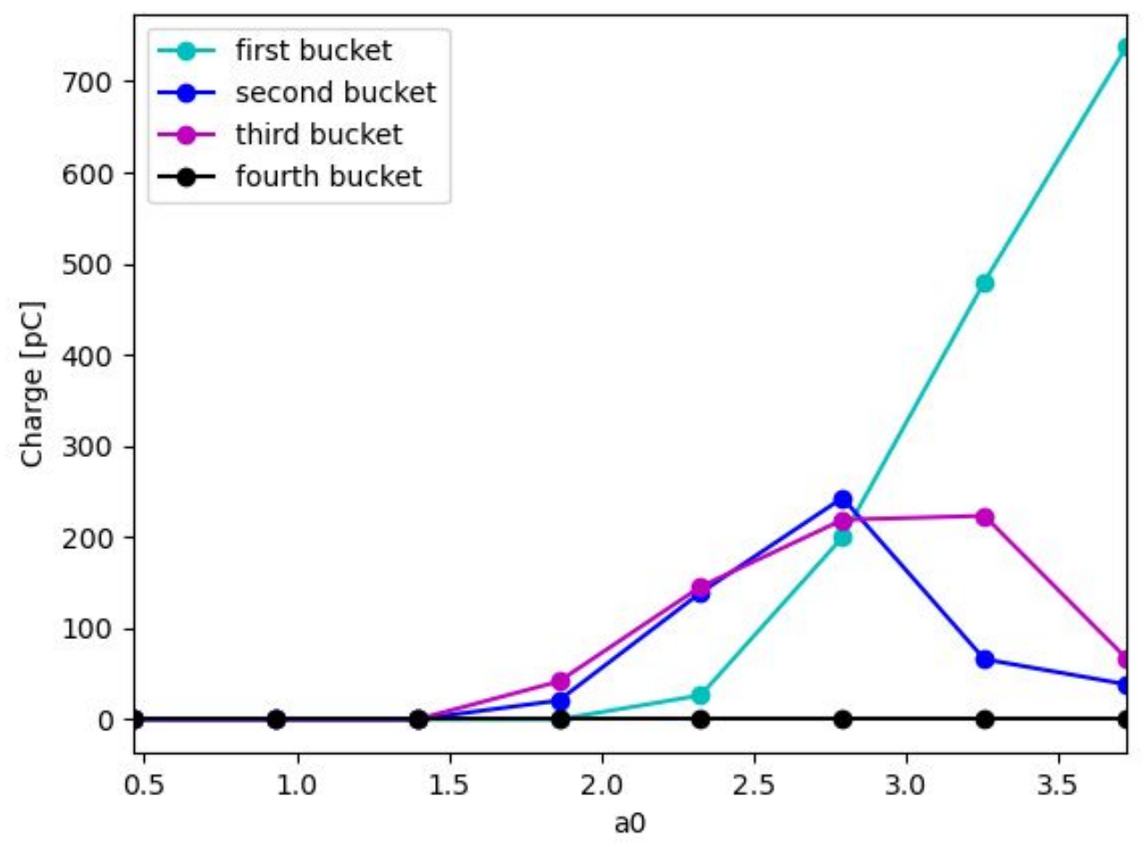

Figure 3. Injected charge in each bucket as a function of laser intensity

When the injected charge within a bucket is very high, the electron bunch can radially repel plasma electrons, driving a wakefield of its own within the laser wake. This phenomena, known as *beamloading*, alters the accelerating structure of the plasma. In the presence of beamloading, the accelerating force felt by the tail of the bunch is typically weaker than that experienced by the head.

These simulations show that when a large charge is injected into the first bucket, the amplitude of following buckets is significantly reduced. The initial injected charge is only high enough to produce this effect when a0 is sufficiently large. This suggests that, in the high intensity regime, beamloading from the first bucket perturbs the wakefield, weakening the accelerating structure and preventing injection in later buckets.

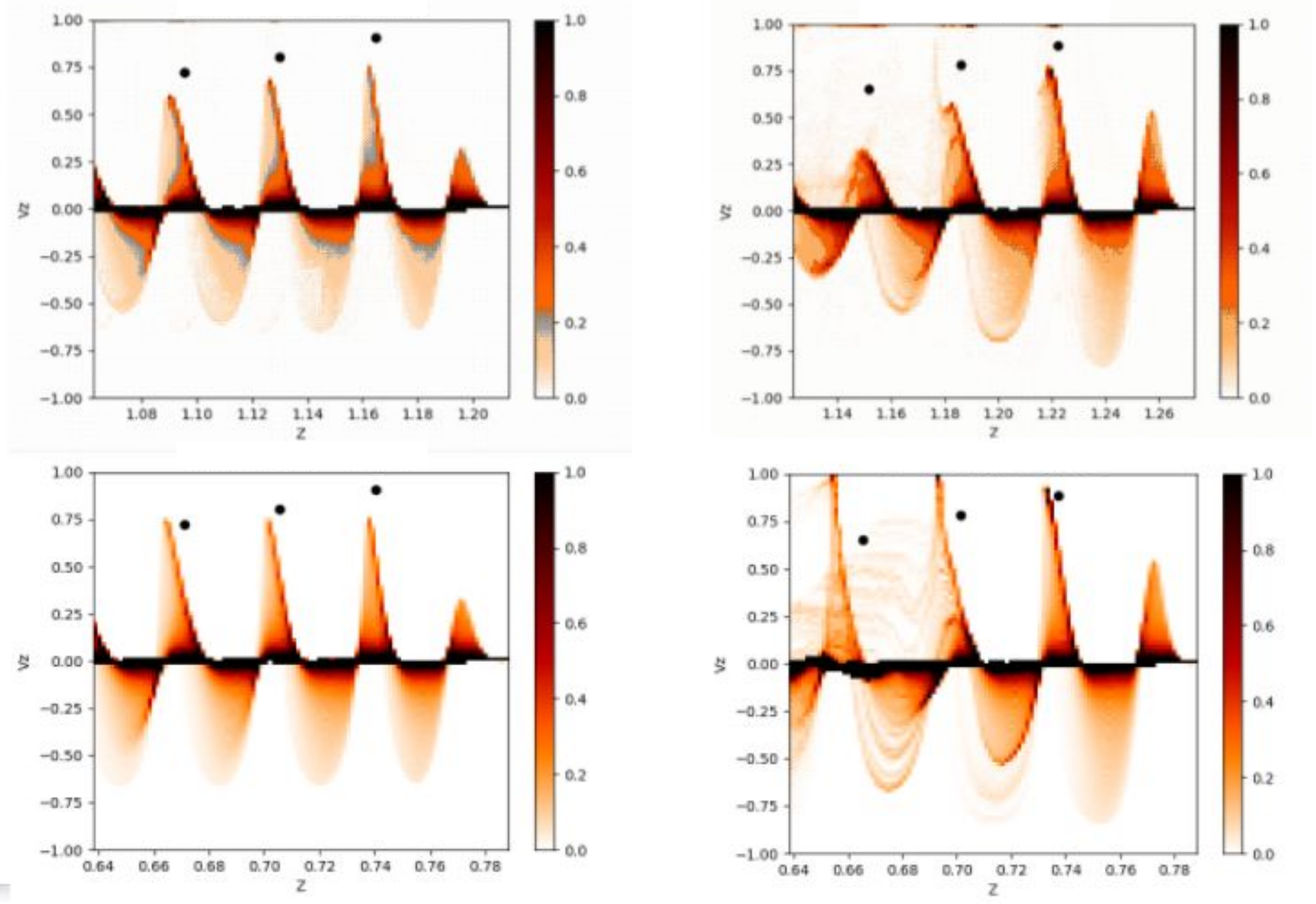

Figure 4. Low intensity regime is depicted on the left panel and high intensity regime on the right. Top plots show the wakefield **with** an injected beam. Bottom plots show the wakefield **without i**njection. Black dots represent the minimum velocity of each bucket.

Conclusion

Beamloading may provide an explanation for the apparent paradox between downramp injection theory and recent experiments. To verify this hypothesis, further research should examine simulation results for specific signatures of beamloading. Additionally, the range of parameters could be extended to explore how this effect varies with background plasma density or other laser conditions.

This material is based upon work supported in part by the Department of Energy National Nuclear Security Administration through the Nuclear Science and Security Consortium under Award Number DE-NA0003996.

National Nuclear Security Administration