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DEVELOPING CRITERIA FOR LASER TRANSVERSE INSTABILITY IN LWFA SIMULATIONS

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Abstract

Laser-driven plasma wakefield acceleration (LWFA) is considered as a potential technology for future colliders and light sources. To make the best use of a laser's power, the laser is expected to maintain a stable propagation. A transverse instability is observed in our previous simulations when a long, intense CO_2 laser propagates inside a plasma [1]. This unstable motion is accompanied by strong transverse diffraction of the laser power and results in the disruption of the ion channel typically used for radiation generation [2]. We investigated the hosing-like instability using the Particle-in-Cell code OSIRIS [3] by modeling the laser portion where this instability is seeded and then evolves. In this proceeding, a criteria will be described that allows for the characterization of the temporal and spatial evolution of this instability.

INTRODUCTION

Plasma wakefield accelerators can reach an accelerating gradient of 50 GeV/m [4]. This is hundreds of times greater than the gradient in conventional ones. To maximize the efficiency of LWFAs, it is required that the laser propagates stably inside the plasma to maintain the high acceleration gradient. One potential application of these advanced acceleration methods is to build light sources with highly collimated x-rays generated inside the plasma ion channels [2]. These channels, which are generated by the interaction of a pico-second laser pulses with plasma, are the primary motivation for the study of such an interaction.However, recent simulations of a picosecond, intense CO_2 laser propagating in plasma have shown evidence of transverse instability in the laser profile [1]. In these simulations, the laser duration $\tau_c >> \lambda_p$, where λ_p is the plasma wavelength. The laser ionizes neutral hydrogen gas and due to the ponderomotive force, it creates plasma density waves. The local index of refraction, $\eta = \sqrt{1 - \frac{\omega_p^2}{\omega_0^2 \gamma_\perp}}$, is modified by the plasma density. Here, $\gamma_\perp = \sqrt{1 + a_0^2/2}$ and $a_0 = eA/mc^2$ is the normalized vector potential, and ω_o and ω_p are the laser frequency and plasma frequency, respectively [5]. Smaller plasma density n_0 corresponds to a larger η. The laser is self-focused [6] and maintains its spot size as it propagates in the plasma. The laser front part, which interacts with plasma earlier, is dominated by the self-modulation instability [6]. In self-modulation, ω_0 is shifted by ω_p to $\omega_0 \pm \omega_p$ from the plasma wave and the laser gets bunched longitudinally. At the back part, where the interaction starts later, the laser is self-channeled [7]. This occurs when plasma ions follow plasma electrons moving away from the axis, and a hollow plasma ion channel, where significant radiation is generated [2], is formed. In the transition region between laser self-modulation at the front and self-channeling at the back, a transverse instability is observed in the laser envelope which resembles the hosing instability of a particle beam in a particle-driven plasma wakefield accelerator [1]. Under this hosing-like instability, the centroid of each longitudinal laser slice oscillates transversely around its propagation axis with growing amplitude. Saturation is reached when the slices have too large an offset to be restored and just move outward away from the axis. The instability extends backwards from the back of the self-modulation section,the process of which diffracts the laser core and disrupts the plasma channel, thus prematurely terminating electron energy gain or radiation processes. To investigate this seeding, we stimulated the portion of the laser that undergoes self-modulation and the hosing-like motion. The properties of this instability were studied using the OSIRIS code in the two-dimensional (2D) geometry [3]. However, the presence of this instability was also confirmed in 3D geometry, demonstrating that this instability is present regardless of the geometry used in the simulations. In this proceeding, we will first introduce our OSIRIS simulation setups. Then, we will explain the criteria that was developed to characterize the evolution of the hosing-like instability both in time, i.e. at the same position in the frame of the laser, and in space, i.e. the evolution along the laser axis.

SIMULATION SETUP

We launched 2D Cartesian simulations with laser propagation direction (z) longitudinally and laser polarization direction (x) transversely. The CO_2 laser had a transverse Gaussian profile and a longitudinal Gaussian-like profile fitted by a 5^{th} order polynomial.

In the simulation, we model a $\lambda_0 = 9.2$ μm laser with 2 ps duration (τ). The spot size W_0 is 20 μm and its normalized vector potential a_0 is 4.3. The simulation uses a moving window traveling in z. Because $c\tau \gg \lambda$, it is challenging

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to simulate the entire laser pulse, while maintaining a resolution below the wavelength scale. To reduce the required simulation time while modeling the region of interest, we restrict the simulation box to a region that contained only a portion of the channel (i.e. the back part), while fully containing the self modulation region (i.e. the front) and the transverse instability region. The size of our simulation box is 0.1 cm (longitudinally) $\times$ 0.02 cm (transversely) with 135 Cells/λ_0 $\times$ 90 Cells/W_0 in both directions. Each cell contains 2×2 particles.

The neutral hydrogen gas started at $z = 0.1$ cm and had a uniform transverse distribution. Its longitudinal profile consisted of a 0.6 cm plateau and two, 200 μm ramps at both ends with a peak density of $n_0 = 7.5 \times 10^{17}\text{cm}^{-3}$. The laser was focused in the middle of the plasma up-ramp and the ionization process was simulated by OSIRIS Ammosov-Delone-Krainov (ADK) tunneling ionization model. Ion motions was also accounted for in our simulations.

CRITERIA FOR INSTABILITY CHARACTERIZATION

As the laser propagates through the plasma, the transverse structure of the pulse evolves both in space and in time (see e.g. Figure 1). We developed the following criteria in order to be able to quantitatively describe this evolution.

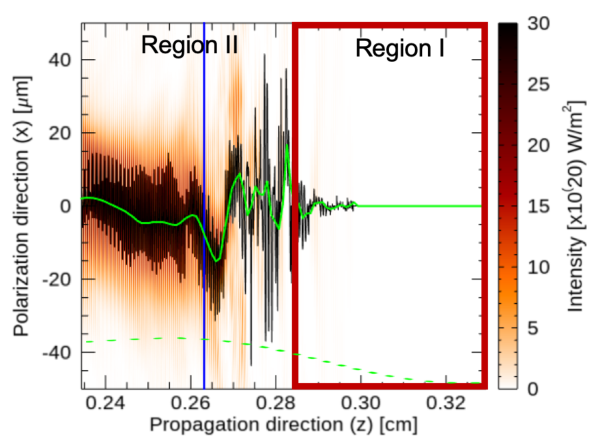

Figure 1: Laser intensity plot at propagation distance z = 0.229 cm. The laser propagates to the right. The averaged centroid (green curve) and non-averaged centroid (black curve) are shown. The green dash line at the bottom shows the laser's initial intensity profile. The laser is self-modulated in Region I (the red box) and it becomes unstable in Region II. The blue vertical line in Region II represents the onset of hosing-like motion at this time.

Intensity Centroid

The hosing-like motion is represented by the transverse oscillation of the laser centroid. The laser centroid for each longitudinal slice i is calculated by $I_c = \frac{\int I \cdot x \mathrm{d}x}{\int I \mathrm{d}x} = \frac{\sum_i I_i x_i}{\sum_i I_i}$, where I is the local intensity of the laser pulse and x is the transverse position of slice i. The slice centroid I_c is shown in Figure 1 with a black line.

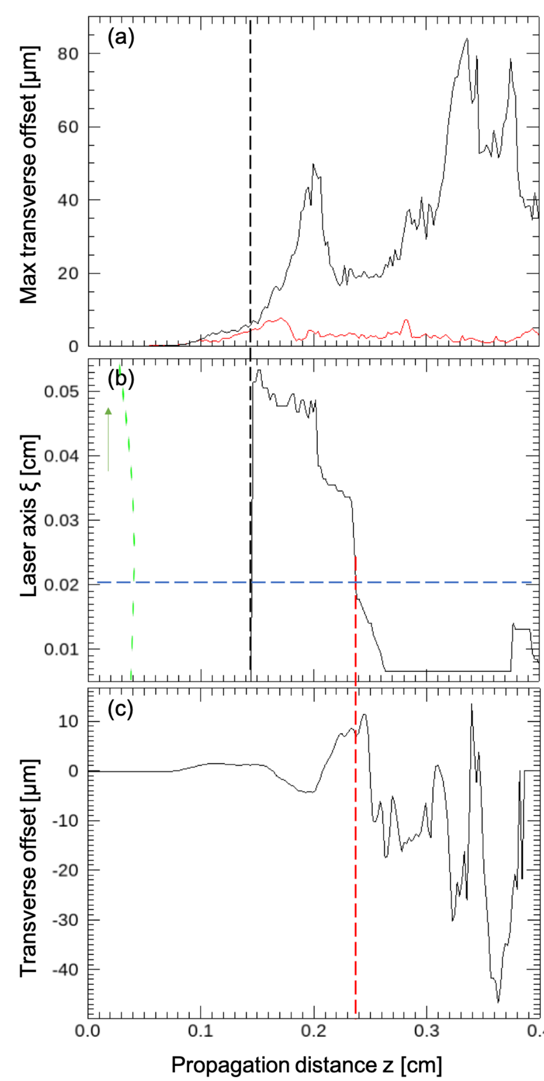

Figure 2: Instability characterization: (a) Maximum absolute centroid offset at self-modulation region (red curve, corresponding to Region I in Figure 1) and at hosing-like region (black curve, corresponding to Region II in Figure 1); (b) Spatial evolution of hosing-like motion along the laser axis ξ = z - ct and (c) temporal oscillation of laser slice at ξ = 0.02 cm (blue dash line in (b)) as functions of laser propagation distance (z). The black vertical dashed lines in (a) and (b) indicate the location at which the two curves in (a) diverge, which occurs when the maximum absolute offset exceeds 6 μm. The green dashed curve in (b) is the initial laser profile (same as the profile in Figure 1). The green arrow indicates laser propagation direction. The red vertical dashed lines in (b) and (c) indicate the location (z_h = 0.238 cm) at which the laser slice with ξ = 0.02 cm starts its hosing-like motion. The horizontal axis was truncated at z = 0.4 cm because the laser energy was depleted by the hosing-like instability after that.

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As shown in Figure 1, the transverse structure of the laser envelope varies spatially on a scale that is much larger than the laser wavelength, λ_0. To smooth out these fast oscillations, the function $I_c(x)$ is averaged over the laser wavelength, resulting in $\overline{I_c(x)} = \frac{\int_0^{\lambda_0} I_c \mathrm{d}z}{\lambda_0}$. This smooth curve shown using a green line in Figure 1, allows for the quantitative characterization of the evolution of the transverse instability.

Onset of Hosing-like Instability

Initially, the laser is self-focused and the centroid of all longitudinal slices lie along the propagation axis at $x = 0$. As the laser propagates through the plasma, the centroid of most slices exhibit some deviation from the axis. While the laser slices at Region I in Figure 1 have deviations within $\pm 10\ \mu$m (as shown in red curve in Figure 2(a)), the absolute offset of slices at Region II continues to grow as the laser propagates in the plasma (as shown in black curve in Figure 2(a)) . The maximum absolute offset for the two regions (black and red curves in Figure 2) starts to separate significantly from each other at around $z = 0.15$ cm (black dashed vertical line in Figure 2(a)(b)), where the absolute amplitude of the offset reaches 6 μm. The offset in Region I (the self-modulation region) saturates at this value, which is about one-half of the laser spot size. This offset value is therefore used as a **criteria** to distinguish the *small* transverse deviation observed for all slices from the *significant* deviation observed in the slices that are participating in the transverse instability.

Using this criteria enables us to observe the evolution of the transverse instability in time and space. Spatially, the amplitude of centroid offset initially increases from the front of the laser pulse to the back, but it decreases back to almost zero again. We interpret the point where the absolute offset of the centroid drops below 6 μm (the threshold value) as the **onset** of this instability. i.e. the laser slices behind the onset have not started participating in the transverse instability yet. The slice that corresponds to the onset of transverse instability in Figure 1 is denoted by a solid blue line.

Evolution of Hosing-like Instability

The motion of the onset of transverse instability along the laser pulse length is observed by tracking its location in the co-moving frame, $\xi = z - ct$, as a function of propagation distance into the plasma, z. This spatial evolution is shown in Figure 2 (b), where the onset of hosing consistently moves backwards at an ever increasing slope throughout the simulation. The growth of the transverse instability towards the back of the laser pulse is accompanied by the disruption of the channel region. The portion of the laser in the front (i.e. Region I in Figure 1) continues to be self-modulated.

Figure 2(c) shows the oscillation of a laser slice at $\xi = 0.02$ cm. When z < z_h = 0.238 cm (as marked by black dashed line in Figure 2(c)), the hosing-like motion has not reached this slice. However, its centroid has small perturbations because the offset of front slices changes the local index of refraction of plasma. The oscillation of this slice speeds up as the laser propagated from 0.1 cm to 0.22 cm as more laser slices started participating in the hosing-like motion. At z > z_h, the slice undergoes the transverse instability and its centroid oscillates with a growing amplitude. The instability erodes the plasma channel and therefore the laser is no longer self-guided.

CONCLUSION

In this proceeding, a criteria is described for identifying the region of the laser that is undergoing the transverse instability. This criteria is based on the examination of the transverse offset of the centroid of the laser from the original propagation axis. Tracking the transverse offset of the laser slices allows one to identify several characteristics of this transverse instability, including the rate at which it moves backwards in the frame of the laser ξ. Future works will be focused on finding the scaling law of the instability with parameters like laser wavelength and plasma density. The growth rate and saturation of the instability will also be compared with theoretical models.

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