Self-modulated laser wakefield acceleration driven by CO_2 laser in hydrogen plasma

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Developments in CO_2 laser technology at Accelerator Test Facility (ATF) of Brookhaven National Laboratory (BNL) has opened the possibility of exploring CO_2 laser driven wakes [1], a regime capable of producing large accelerating structures, enabling better probing of wakes and precise external injection. Long wavelength $(9-11\mu m)$ of CO_2 laser has certain inherent advantages over widely used solid state lasers having wavelengths $(0.8-1\mu m)$. These mid-IR lasers, thanks to favorable wavelength scaling, are more efficient at driving plasma waves and ultimately could drive fully blown out plasma bubbles with dimensions of several hundreds of microns, in plasma densities on the order of $10^{16} cm^3$. This would relax the conditions for external injection, leading to extremely small emittances and energy spreads. Currently, the ATF delivers laser pulses of 4 J energy and 2.0 ps FWHM duration, that allows the exploration of CO_2 laser driven self-modulated laser wakefield acceleration (SM-LWFA). Studying the interaction of CO_2 laser with hydrogen jets has been the recent focus of experiment AE-71 in which self-modulated wakes have been observed for a range of plasma and laser parameters [2].

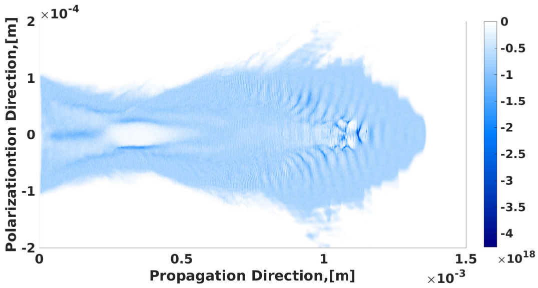
In this contribution, 3D numerical simulations investigating the evolution of laser and plasma wakes at parameters motivated by experiment AE-71 are presented. Parallel relativistic Particle-in-Cell code SPACE has been used in these studies. SPACE is a general purpose electromagnetic PIC code with novel atomic physics algorithms to resolve ionization, recombination and other atomic physics transformations [3, 4]. Reproduction of experimentally observed Stokes and anti-Stokes sidebands and their dependence on gas density was reported before and several experimental trends were explained through SPACE simulations [5]. In this paper we have shown that the front portion of the long ($\sim$ ps) CO_2 laser undergoes self-modulation instability and the rear portion self-channels when the ionization model with mobile ions is used. Role of ion-motion on the plasma dynamics has been studied and comparisons with stationary ion case has been presented. In addition, formation of ion-density maxima on the axis of the channel has been observed and analyzed.

Current laser parameters allow the laser to undergo self-modulation triggered by forward

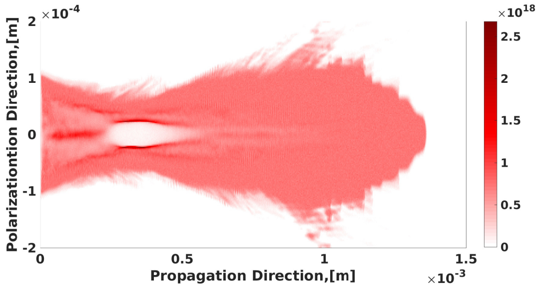
Energy	Wavelength	Beam Waist	Duration	Focus Position
4 J	9.2 μm	20 μm	2.0 ps(FWHM)	400 μm

Table 1: *Laser Parameters*

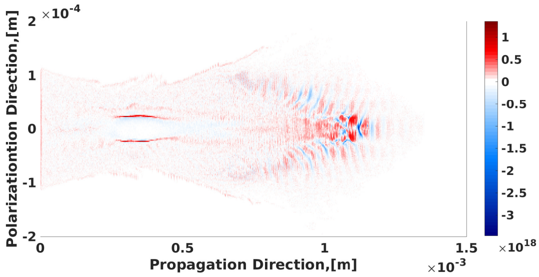
Raman scattering instability. The interaction creates relativistic electron plasma waves and the laser (k_0) manifests itself into Stokes and anti-Stokes sidebands ($k_0 \pm nk_p$) where n is an integer. Here k_0 is laser wavenumber and k_p the plasma wavenumber. As the laser propagates further in the gas-jet, laser strength parameter, a_0, increases further due to relativistic self-focusing and the interaction becomes highly nonlinear. A channel like structure is created in plasma behind the SM-wakes and plasma reaches quasi neutral state (Figure 1(c)). These properties were also observed in simulations conducted with OSIRIS [6].



(a) *Electron Density*



(b) *Ion Density*

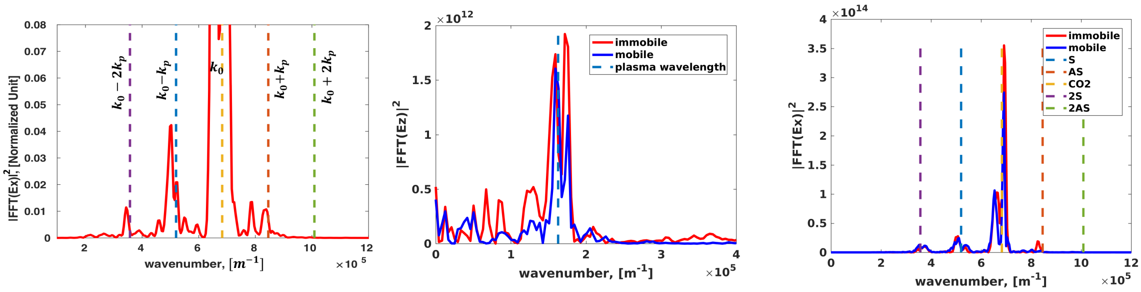


(c) *Total Charge Density*

Figure 1 : (a) Electron density plot showing the evolution of plasma wakes. (b) Ion Density (c) Total charge density showing quasi neutral state of plasma when ion motion is strong. Linearly polarized laser, with focus position at 0.4 *mm is propagating from left to right and the center has reached* 0.9 *mm. Plasma number density is assumed to be* 7.5×10^{17} cm^{-3}.

We have performed 3D SPACE simulations to confirm these physical effects and the trends observed in the experiments. A linearly polarized laser pulse, with Gaussian transverse and longitudinal profile having parameters as in Table 1, is injected through the left boundary of the simulation box of size 400×400 μm in transverse direction and 3.0 mm in longitudinal direction.

Hydrogen gas is assumed to be uniformly distributed from zero to 1.5 mm in longitudinal



(a) *Normalized transverse field intensity.* (b) *Comparison of longitudinal field intensities* (c) *Comparison of transverse field of intensities*

Figure 2: *(a) Intensity spectrum of the laser after interaction showing Stokes and anti-Stokes signals. (b) and (c) Both longitudinal and transverse field amplitudes are suppressed when ions are mobile. In addition, early saturation of self-modulation instability is evident in reduction of sideband amplitudes in mobile ion case (c).*

direction and tunneling ionization algorithm based on ADK model is used to create plasma as the laser propagates. 20 cells per beam waist in the transverse direction and 20 cells per laser wavelength in longitudinal direction have been used. Simulations utilize 32 particles of each species per cell when the gas is fully ionized. Both stationary and mobile ion cases were simulated. Numerical dispersion studies have confirmed that this resolution is sufficient for targeted problem.

Figure 1a shows the evolution of plasma wakes when the laser center has reached 0.9 *mm*. As laser propagates through jet, laser strength increases through relativistic self-focusing and it drives relativistic plasma waves. Clear SM-wakes are seen in the front part. Further focusing of the laser pulse makes the interaction highly nonlinear and several irregular wakes are created due to wave breaking. Ions do not react to the laser in the initial rising portion of the laser pulse, but start moving once laser energy becomes sufficient and are expelled radially from the center and an ion channel is formed (Figure 1b). Intensity spectrum of the laser was calculated after it completely exited plasma and is shown in Figure 2a. Two sideband peaks at $k_0 \pm k_p$ and $k_0 - 2k_p$ can be seen. Here k_0 and k_p are laser and plasma wavenumbers respectively. Peaks on the right are relatively weaker. Role of ion-motion on this dynamics was also investigated and findings were compared with previous study [7]. A simulation with same physical and numerical setting was run, but ions were assumed to be stationary. Amplitudes of longitudinal and transverse fields were compared and the results are shown in Figure 2b and 2c respectively. Ion-motion suppresses the focusing forces and causes early saturation of self-modulation instability compared to the case where ions are stationary. Longitudinal accelerating field amplitude in the case

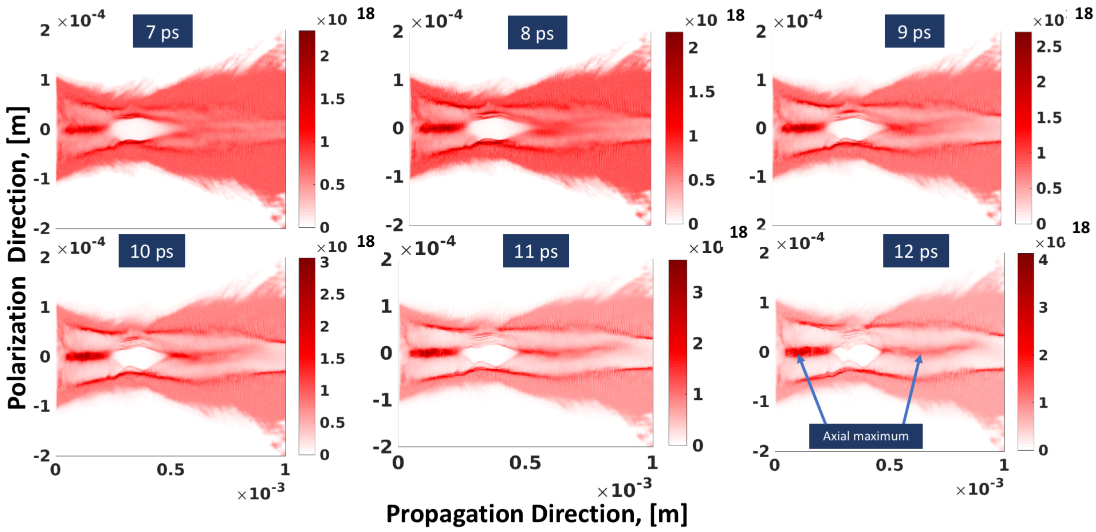


Figure 3: *Formation and evolution of ion density maxima on the axis of the channel.*

of mobile ions is also suppressed compared to the stationary ions case as shown in Figure 2b.

In addition, long-term evolution of the wake structure in the region of gas jet shows ion density maxima formation created by the radial attractive forces of the wake itself. Two axial density maxima, one on the left of the laser focus position and one on the right, were observed as shown in Figure 3. Once the maxima is formed, interaction reaches quasi steady state, as evident in six temporal snapshots, 1.0 ps apart, as shown in figure 3. At the focus position there is a region with effectively zero ion/electron density. This has been attributed to the fact that ponderomotive force is largest at the laser focus. Modeling the effects of experimental imperfections including gas-jet density and laser profile is a part of our ongoing effort.

We have studied the interaction of TW-peak CO_2 laser with hydrogen jets for various physical and numerical parameters. Observation of SM-wakes in experiments have been confirmed through 3D SPACE simulations and the role of ion motion on the dynamics of plasma has been investigated.

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