Expanded Model Predictions for Seeded SM-LWFA and Pseudo-Resonant LWFA

N. E. Andreev,[§] S. V. Kuznetsov,[§] A. A. Pogosova,[§]
L. C. Steinhauer,[¶] and W. D. Kimura[*]

[§]*Institute for High Energy Densities, Russian Academy of Sciences, Moscow 125412, Russia*

[¶]*University of Washington, Redmond Plasma Physics Laboratory, Redmond, WA 98052 USA*

[*]*STI Optronics, Inc., Bellevue, WA 98004 USA*

Abstract. A laser wakefield acceleration (LWFA) model has been upgraded to better predict the outcome of experiments to test two new LWFA techniques. The first method is seeded self-modulated LWFA where an ultrashort electron bunch acts as a seed to create a wakefield in a plasma, which is subsequently amplified by the laser pulse. The second scheme is pseudo-resonant LWFA where nonlinear pulse steepening of the laser pulse by the plasma allows generation of a significant wakefield. A witness bunch that probes the wakefield was incorporated in the model. The model was also exercised to examine new operational regimes currently available during the experiments.

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INTRODUCTION

The Staged Electron Laser Acceleration – Laser Wakefield (STELLA-LW) experiment [1] is in the process of investigating two new laser wakefield acceleration (LWFA) schemes – seeded self-modulated LWFA (seeded SM-LWFA) [2] and pseudo-resonant LWFA (PR-LWFA) [3]. The former technique uses a seed electron bunch. For both methods, a witness electron bunch would nominally follow to probe the wakefield. The experiment is being performed at the Brookhaven National Laboratory Accelerator Test Facility (BNL-ATF).

To study these new operating regimes in more detail, the LWFA model was upgraded to include the seed and witness bunches. Inclusion of the seed bunch effects is straightforward because the bunch mimics plasma wakefield acceleration (PWFA) as it generates its wakefield. Inclusion of the witness bunch is more complex because the witness electrons must travel through the beginning of the plasma region where the wakefield has not formed yet. Therefore, any plasma effects on the witness electrons while traversing through this region had to be included.

The STELLA-LW experiment has also been making steady progress in its preparations to perform the experiments. Ultra-low plasma densities ($<10^{15}$ cm^{-3}) have been demonstrated, which opens up new possible operating scenarios. There is a better understanding of the limitations of the present experimental apparatus. This

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provides updated parameter values for the experimental conditions that can be simulated by the model.

This paper reviews the results of these expanded model simulations and how their results impact the future direction of the STELLA-LW experiment.

SEEDED SM-LWFA MODELING

Seeded SM-LWFA was originally called stimulated LWFA [4] and is a close cousin of Raman seeding [5], [6]. The latter uses a second low-intensity frequency-shifted laser pulse, which provides a seed for the main laser pulse self-modulation and does not rely on noise to generate the wakefields. In seeded SM-LWFA, an ultrashort *e*-beam bunch precedes the laser pulse to generate a moderate strength wakefield that the laser pulse subsequently amplifies via a self-modulation process. A key aspect of this technique is that the wakefield generated by the seed *e*-beam bunch does not start from noise as is typically the case in SM-LWFA. Instead, the model simulations indicate the wakefield phase is closely tied to the arrival time of the seed bunch. The laser pulse simply amplifies this wakefield without significantly changing its phase. Thus, this method may enable more controllable wakefield generation, thereby greatly facilitating the staging of these devices.

Figure 1 shows an example of the relationship between the seed and witness bunches, the laser pulse (with and without the seed bunch), and the resultant wakefield generation and amplification. We observe the wakefield generation begins with the arrival of the seed bunch. Self-modulation of the laser pulse starts to occur once the wakefield begins to emerge. Consequently, the wakefield potential also increases in magnitude. In this particular example, the witness bunch probes the wakefield 12 ps after the seed.

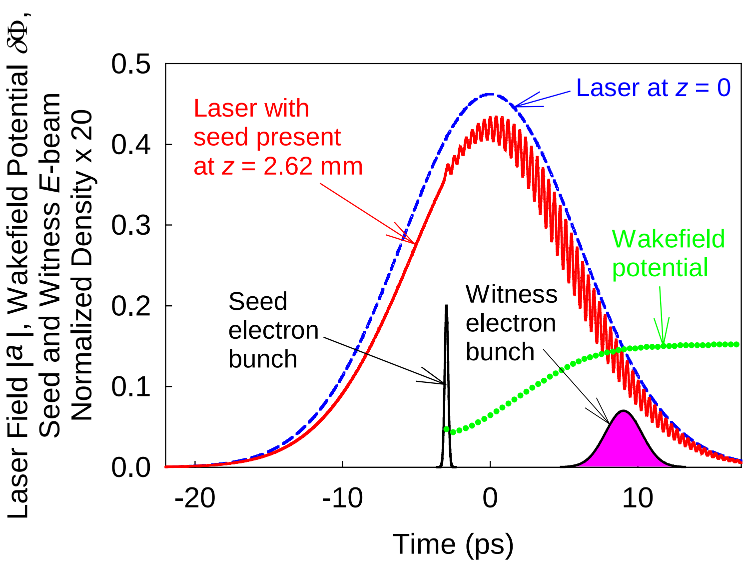

FIGURE 1. Model prediction for laser field parameter $|a(r = 0)|$ and wakefield potential $\delta\Phi(r = 0)$ as a function of time for $z = 2.62$ mm and a time delay between the seed bunch and laser pulse of $t_d = 2.97$ ps. Also plotted are the seed and witness *e*-beam bunch positions for a time delay between the seed and witness bunch of $\tau_d = 12$ ps. All times are referenced to the peak of the pulses.

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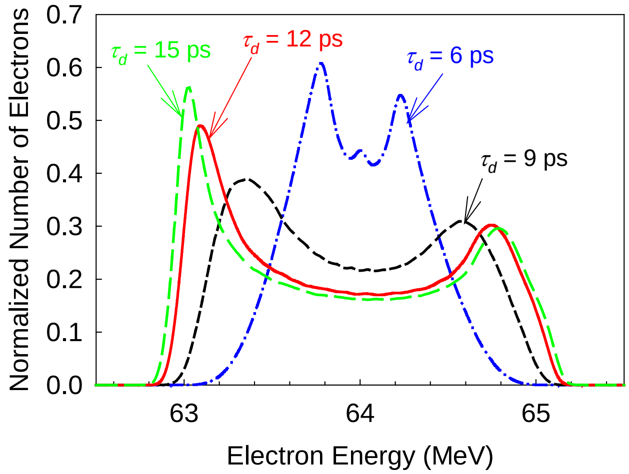

FIGURE 2. Model prediction for energy spectrum of witness bunch for t_d = 2.97 ps and different time delays between the seed and witness *e*-beam bunches for an acceleration length L_{acc} = 2 mm.

Figure 2 shows the predicted energy spectrum of the witness bunch for an acceleration length of 2 mm and at different time delays between the seed and witness bunches. The spectrum shows fairly symmetric double-peaks caused by energy modulation of the witness electrons distributed over all phases of the wakefield. It is very similar to the modulation observed during the STELLA program when using inverse free electron lasers (IFEL) [7]. In fact, if these energy-modulated electrons are allowed to drift or are sent through a chicane, they would form microbunches just as during the earlier STELLA experiment. The key difference is the microbunches would be spaced apart by the plasma wavelength (~300 μm) instead of the laser wavelength (10.6 μm) and they would have a bunch length of roughly ~30 μm rather than ~1 μm. These microbunches would be well suited for injecting into subsequent LWFA devices for trapping and further acceleration, again analogous to what was demonstrated during the STELLA program with IFELs.

In Fig. 2, the maximum accelerated witness electrons gain about 1 MeV over 2 mm corresponding to an acceleration gradient of 500 MeV/m. This was for a laser peak power of 0.5 TW. While this gradient is on the low side compared to typical SM-LWFA devices, it is perfectly acceptable for an LWFA buncher since an energy modulation of order ±1% is only needed. Indeed, if the gradient were too high, it would make it difficult to control the amount of modulation. Nonetheless, a gradient of 500 MeV/m is over 100 times higher than what was obtained using an IFEL [7].

The seeded SM-LWFA process is certainly capable of reaching acceleration gradients similar to non-seeded SM-LWFA devices. Scaling to longer acceleration lengths is also possible just as with non-seeded SM-LWFA. For example, for a slightly different configuration, but still assuming only 0.5 TW laser peak power, the model yields an acceleration gradient of 2 GeV/m over a 3 mm distance.

The STELLA-LW experiment is currently using a capillary discharge with an estimated effective plasma length of 3 mm. Therefore, with 0.5 TW laser power, we can expect to observe ~6 MeV energy gain.

EXPANDED PSEUDO-RESONANT LWFA MODELING

Pseudo-resonant LWFA [3] takes advantage of nonlinear pulse steepening of the tail of the laser pulse as it interacts with the plasma. This steepening effect effectively makes the laser pulse appear like a shorter pulse to the plasma and, therefore, closer to resonance. The net result is that strong wakefields can be generated even though the laser pulse length is too long to satisfy the normal resonant LWFA condition. Another way to look at PR-LWFA is it is operating in a laser pulse length regime that is too long for resonant LWFA, but too short for SM-LWFA.

In principle, PR-LWFA is a simpler experiment to perform compared to seeded SM-LWFA. It requires only a witness *e*-beam bunch following the laser pulse and the bunch length can be its nominal 3-5 ps duration. Initial modeling of the PR-LWFA effect assumed 3 TW laser peak power and ~10^{16} cm^{-3} plasma density [3]. However, the ATF CO_2 laser currently produces 1 TW (5 J in 5 ps). Fortunately, plasma densities lower than 10^{15} cm^{-3} have now been realized at the ATF [8]. Being able to reach 10 times lower density means the 5-ps ATF CO_2 laser pulse can now be closer to the resonance condition and, hence, might be able to generate appreciable wakefields even though the laser peak power is smaller.

The LWFA model was exercised assuming 1 TW laser power, a plasma density of 0.32×10^{15} cm^{-3}, and a plasma length of 3 – 12 mm. We find the wakefield potential starts off fairly weak and drops off with distance. The problem is because the channel radius (300 μm) is very wide in comparison with the matched one (for the assumed density it should be about 60 μm), the laser pulse diffracts and its intensity decreases with distance along the channel.

This effect is shown more clearly in the predicted wakefield potentials and acceleration gradients. For 3-mm propagation distance, we observe very little, if any, pulse steepening occurring on the trailing side of the laser pulse. The peak acceleration gradient is less than 50 MeV/m, which for a 3 mm length would yield too little energy modulation to be easily observable. Increasing the plasma length to 12 mm does not help because of the laser beam diffraction. Therefore, at too low of plasma densities, the laser pulse/plasma interaction is in a linear regime and the nonlinear pulse steepening effects are negligible. Or put another way, the modeling confirms that the minimum required laser power to drive PR-LWFA is 3 TW.

Fortunately, additional modeling analysis has also shown for 3-TW laser power that it is not necessary to use a 6 cm or longer plasma channel to observe good energy gain. Table 1 lists the parameter values used to investigate 1-3 cm long plasma lengths. The parameter values of the witness *e*-beam bunch are (recall there is no seed bunch for PR-LWFA): Energy of injection, $E_{inj} = 64\,\text{MeV}$; pulse duration, $\sigma_t = 1.23\,\text{ps}$; energy spread, $\sigma_E = 0$; and the pulse width was varied from $\sigma_r = 10$ μm to 20 μm. The time delay between the laser pulse and the witness *e*-beam pulse equals 3 ps.

Figure 3 shows an example of the wakefield potential $\delta\Phi$ generated and the resultant acceleration gradient G_z for a distance of 1 cm into the plasma. Note a peak acceleration gradient of >500 MeV/m occurs within the witness pulse.

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TABLE 1. Parameters for short-plasma-length modeling of PR-LWFA.

Parameters	Value
Laser wavelength, λ_L	10.6 μm
Laser pulse duration, τ_L [(a)]	1.69 ps
Laser peak power, P_L	3.0 TW
Laser pulse energy, E_L	6.3 J
Laser beam focus radius, w_0	125 μm
Laser beam Rayleigh range, z_R	4.64 mm
Normalized laser field strength, a_0	1.0
Plasma length [(b)]	1-3 cm
Plasma channel radius, R_{ch}	202 μm
Plasma density on axis, n_0 [(c)]	1.1×10^{16} cm^{-3}
P_L/P_{crit} (for self-focusing)	0.2

[(a)]The full-width-at-half-maximum pulse duration of the laser intensity is equal to

$\tau_{FWHM} = 2\sqrt{\ln 2}\ \tau_L = 1.99$ ps .

[(b)]The plasma length is assumed to be the same as the capillary length.

[(c)]The plasma density is assumed uniform over the entire plasma length.

Figure 4 shows the energy spectrums of the witness bunch with radius σ_r = 20 μm for acceleration lengths L = 1, 2, and 3 cm. Figure 5 are the energy spectrums for a smaller witness bunch radius of σ_r = 10 μm. Even for 1-cm acceleration lengths, peak energy gains of ≈1 MeV are predicted, which are easily observable. The spectrums exhibit more pronounced accelerated and decelerated peaks as the witness bunch radius decreases.

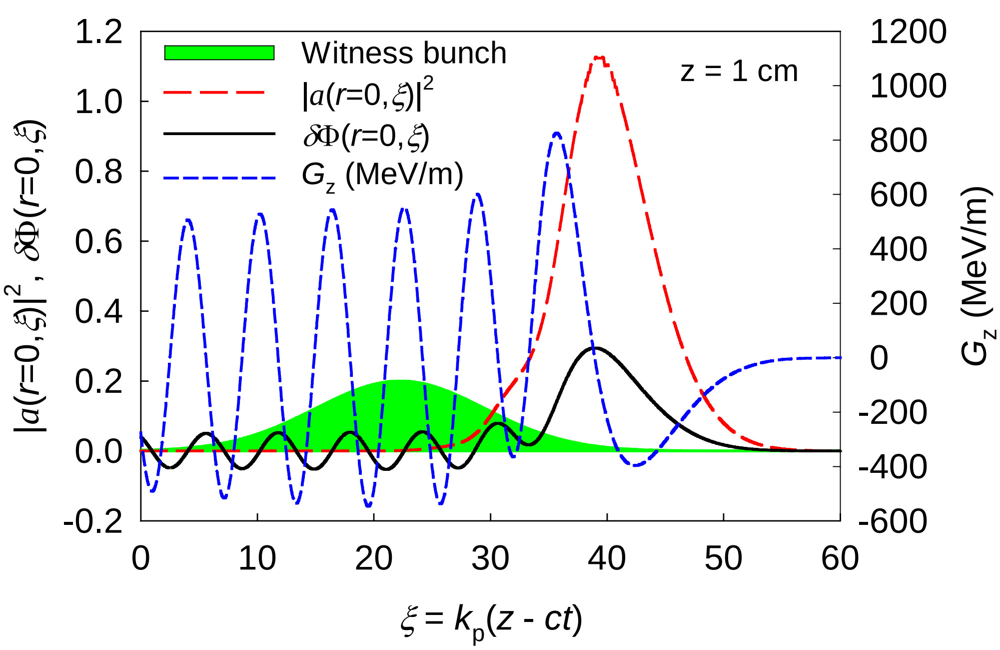

FIGURE 3. PR-LWFA model prediction for laser field parameter $|a(r = 0)|$ and wakefield potential $\delta\Phi$ (r = 0) as a function of time for a propagation distance z = 1 cm. The accelerating (decelerating) gradient G_z in the wakefield on the channel axis is also plotted. Also shown is the witness electron bunch position.

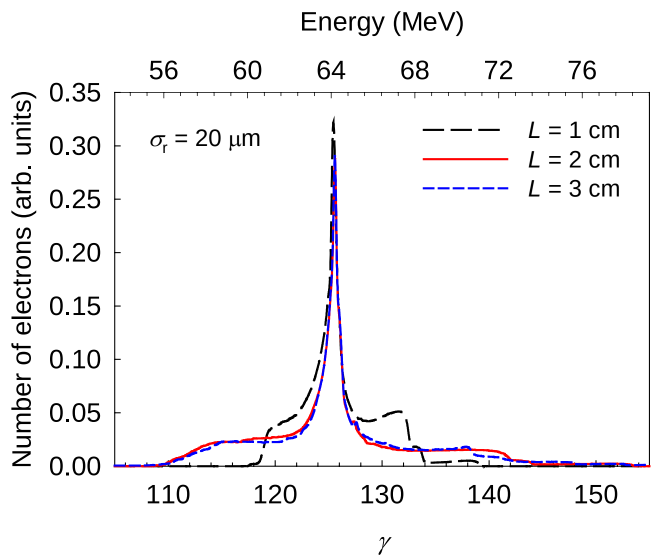

FIGURE 4. PR-LWFA model prediction for energy spectrums of witness electrons as a function of acceleration length for a witness bunch radius of $\sigma_{\mathbf{r}} = 20$ μm.

Comparison of these figures evidently indicates that the primary reason for the large central peak in the energy spectrums in Fig. 4 is due to radial forces, which push the electrons out from the accelerating/decelerating forces before the electrons can change their energy noticeably.

These latest PR-LWFA model results for a 1-cm long plasma length helps ease the requirements for a proof-of-principle demonstration of PR-LWFA since it is easier to operate a 1-cm long capillary than a much longer one. Nevertheless, one of the future goals of the STELLA-LW experiment is to eventually utilize ~5 cm long capillaries in order to demonstrate high energy gains.

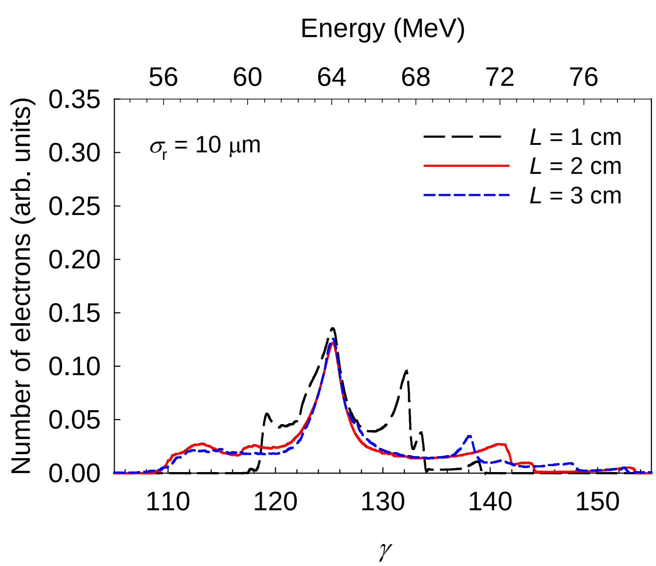

FIGURE 5. PR-LWFA model prediction for energy spectrum of witness electrons as a function of acceleration length for a witness bunch radius of $\sigma_{\mathbf{r}} = 10$ μm.

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CONCLUSIONS

Expanded model simulations for the seeded SM-LWFA and pseudo-resonant LWFA experiments have been performed in order to better match the current experimental conditions. For seeded SM-LWFA, the present CO_2 laser peak power of 1 TW is more than adequate for a proof-of-principle demonstration. An energy modulation of ≈±1 MeV of the witness electrons is expected for 0.5 TW laser power. However, due to the unexpected formation of a double-bunch seed from the ATF linac system [9], demonstration of the seeded SM-LWFA effect will be initially done by observing an increase in the Raman sideband signal from the laser light scattering off the wakefield (see [1] for details). Afterwards, the more complicated procedure of performing the experiment with the double-bunch seed and witness bunch will be pursued.

For PR-LWFA, the model confirms that a minimum of 3 TW is necessary to drive the process. Therefore, the present laser peak power needs to be increased from 1 TW to 3 TW. The ATF is currently upgrading their laser systems in order to increase the CO_2 laser peak power. We anticipate that 3 TW may be available sometime in 2008 (see [1] for more details).

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