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Analysis of Laser Wakefield Acceleration Using ATF CO_2 Laser

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Abstract. In projections of laser wakefield acceleration (LWFA), long laser wavelength presents major advantages. A new opportunity for exploiting this promise is offered by a forthcoming upgrade at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). The CO_2 laser is being upgraded to deliver >1 TW peak power with ~2-ps laser pulse length. With this upgrade, promising LWFA experiments at 10.6 μm will be possible. These experiments will also exploit the availability of equipment for generating plasmas by capillary-discharges at the ATF. This will enable acceleration over extended lengths without invoking self-focusing. Analytical modeling and numerical simulations are presented to evaluate the potential for such experiments with a long-wavelength laser. A major issue in LWFA is wake controllability and regularity, and the achievement of small energy spread. Here, the insights gained from controlled staging experiments during the STELLA program at the ATF will prove valuable. A possible embodiment for achieving this is the stimulated LWFA concept introduced here.

INTRODUCTION

High-gradient acceleration of electrons has been achieved in laser wakefield acceleration (LWFA) experiments using solid-state lasers; see e.g., [1]. Moreover, the advantages of long wavelength lasers, such as the 10.6 μm wavelength CO_2 laser for LWFA, have been noted [2]. A factor of 10 increase in the laser field parameter and a factor of 100 increase in the ponderomotive potential are gained at 10.6 μm. No experiments, however, have yet been conducted to exploit these advantages. Here a unique opportunity is presented by the Accelerator Test Facility (ATF) at Brookhaven National Laboratory, particularly in view of the availability within the next few months of an upgraded CO_2 laser with >1 TW peak power in a ~2-ps laser pulse. Also available is a capillary-discharge plasma system to enable channeling the laser-plasma interaction over a distance much longer than the Rayleigh range.

We have applied analytical models of LWFA to investigate the potential for performing experiments on the ATF. The second section describes the ATF parameters and how they might be exploited to explore LWFA. A key watchword here is the need to grow a wake in a regular and ultimately a controlled manner. This is in the same spirit as the recent STELLA experiments [3] in which staged laser acceleration was achieved.

Multi-dimensional numerical results are presented in the third section. These preliminary results indicate that strong wakes >1 GeV/m can be produced over >5 cm lengths by the upgraded CO_2 laser on the ATF.

A possible embodiment for controlled LWFA experiments on the ATF is introduced in the fourth section. This *stimulated LWFA* concept, uses a seed-wake generated by a separate short-pulse laser or *e*-beam. This purports to improve wake regularity and allow the phase control needed in a staged accelerator system.

ELEMENTS OF LWFA AT LONG LASER WAVELENGTH

The normalized laser field parameter is $a_0 \propto (\lambda_0/r_0)P^{1/2}$ where λ_0, r_0, and P are the laser wavelength, spot size, and power. On the basis of laser focusing alone there is no wavelength advantage since $r_0 \propto \lambda_0$ in a diffraction-limited focus. However, the useful spot size is probably set by the *e*-beam size since the r_0 must exceed r_b, the *e*-beam radius, in order to achieve small energy spread. For a long *e*-beam focus, $r_b \sim$ 50 – 100 μm. Since r_0 is set by *e*-beam considerations, the proportionality $a_0 \propto \lambda_0$ favors long wavelength lasers. Thus for the same spot size and power a CO_2 laser with λ_0 = 10.6 μm has ten times higher a_0 than solid state lasers with λ_0 = 0.8 – 1 μm.

Another difference for a long wavelength lasers is a lower critical density $n_c \propto \lambda_0^{-2}$, which is *two* orders of magnitude lower for CO_2 lasers. This favors lower electron density n_e, which is also favored by other factors. A goal is to maximize the number of electrons per bunch. This maximum is set by the condition that the space charge field of the bunch not compromise the wakefield structure. This, as well as the condition of small energy spread of the accelerated electrons [electron bunch much shorter than the plasma wake period, $\tau_b << 2\pi/\omega_p$ ($\omega_p \propto n_e^{1/2}$ is the plasma frequency)] favors lower density. Although the acceleration gradient ($\propto n_e^{1/2}$) is smaller at lower density, longer dephasing distance $L_{ph} = \lambda_p^3 / \lambda_0^2 \propto n_c / n_e^{3/2}$ ($\lambda_p \equiv \omega_p/c$ is the plasma wavelength) allows the same maximum electron energy gain to be achieved. This maximum is independent of the plasma density and laser wavelength. (This is under the condition of fixed laser pulse group velocity, which is determined by the ratio n_c/n_e).

Design philosophy

In designing a LWFA experiment on the ATF, the guiding principle is the ability to scale to practical accelerator conditions. Toward this end the goals of the envisaged experiments are the following. (1) *Extended interaction length*. A long interaction length is needed for each section in a practical laser-accelerator. Otherwise the accelerator length is dominated by the spaces between sections needed for laser beam injection and the plasma generation system. Hence, a plasma length L_p = 10 cm is chosen as the goal. This is an order of magnitude longer than in most previous experiments. (2) *Controllability*. This is essential in a practical, many-sectioned accelerator system. Multi-staging requires a *regular wake* to avoid degrading the beam quality. It also requires a controllable wake phase in order to synchronize successive sections. This is necessary so that particles accelerated by one section can continue to be accelerated and possibly focused. The goal then is to operate *below* the self-focusing threshold $a_0 = 0.9\lambda_p/r_0$, above which the interaction becomes nonlinear and hard to control. Simulations of self-modulated (SM) LWFA [4] above the self-focusing threshold, exhibit highly irregular wakes that are unsuitable for controlled acceleration. (3) *Separate laser channeling and wake growth*. These functions (which are mixed in SMLWFA) should be kept separate to improve control. Thus, a focusing channel must be provided independently in order to guide the laser over the full plasma length. (4) *Good acceleration gradient*. In order for the experiment to be of value, a good acceleration gradient should be achieved, namely >1 GeV/m.

Capabilities of the ATF

The Accelerator Test Facility at Brookhaven offers a high-power long-wavelength CO_2 laser, a high-quality electron beam of moderate energy, and capillary-discharge plasma equipment. The relevant parameters of the ATF are shown in Tab. I.

TABLE I. Accelerator Test Facility Parameters.

Laser (λ = 10.6 μm)	**Current**	**Upgrade or Planned**
Pulse energy	5 J	5 J
Pulse length	180 ps	~2 ps
Power	25 GW	2.5 TW
Electron beam		
Energy	≤72 MeV ($\gamma \leq 140$)	
Normalized emittance	~2 mm-mrad	
Macrobunch charge	≤0.5 nC	
Macrobunch length	3 ps	300 fs
Capillary discharge plasma		
Channel diameter		200 μm – 1 mm
Density		$>10^{16}$ cm^{-3}
Electron temperature		5 – 10 eV

The upgraded 2-ps laser pulse is intermediate between that needed for "resonant" LWFA (~ 0.4 ps for a density of $n_e = 10^{16}$ cm^{-3}) and the relatively long pulse Neptune laser at UCLA (40 ps). The high-quality ATF e-beam will produce bunches as short as 300 fs with the forthcoming bunch-compressor modification. Laser channeling has already been demonstrated in capillary-plasma discharges at the ATF [5].

Possible mechanisms of wakefield generation

Consider the potential of standard "resonant" LWFA for wake generation. The amplitude of the one-dimensional wakefield generated by this mechanism is

$$|E_w| \;=\; \frac{m_e c^2}{e} k_p \frac{|a_0|^2}{4} \cdot h_{1D}\,, \tag{1}$$

where h_{1D} is the wake generation efficiency. For a Gaussian laser pulse,

$$h_{1D} \;=\; \pi D \exp\left(-\pi D^2/4\right), \tag{2}$$

where $D = 2c\tau_L/\lambda_p$ is the detuning parameter and τ_L is the laser pulse duration. For a density $n_e = 10^{16}$ cm^{-3}, and a laser field parameter $a_0 = 0.8$, the wakefield amplitude is $|E_w| = 1.54 \cdot h_{1D}$ GV/m. However, the efficiency for the 2-ps pulse length is only $h_{1D} = 0.04\%$, giving a wakefield of 0.7 MV/m. Nonetheless, if the pulse length were shortened to $\tau_L = 0.97$ ps, i.e., slightly more than a factor of two, then the efficiency would increase dramatically to $h_{1D} = 50\%$. Effective pulse shortening can be accomplished by a pulse leading-edge steepening effect. Such an effect may play an important role, as suggested by the numerical results presented later.

Raman forward scattering (RFS) is a wake amplification mechanism. As analyzed elsewhere, e.g., [6], the maximum wake growth occurs for ω_p/k equal to the group velocity of the laser pulse amplifying the wake. The maximum growth rate assuming a one-dimensional, four-wave interaction (pump, Stokes, plasma wave) is

$$\gamma_{\max} \;\approx\; \left(1/\sqrt{8}\right) a_0 \omega_0 \left(n_e/n_c\right). \tag{3}$$

The RFS mechanism amplifies a wake by e^G where G is the gain exponent. With spatial-temporal effects (finite pulse length and plasma length) [6],

$$G \;\approx\; (4/3)\gamma\sqrt{\tau_L L_p/c}\,. \tag{4}$$

This "averaged" value accounts for the variation from the upstream to downstream ends of the plasma; G is assumed to be 2/3 of the larger (downstream) value. Note that the laser transit time through the plasma L_p/c figures equally with the laser pulse length τ_L. For a density $n_e = 10^{16}$ cm^{-3}, a CO_2 laser with $a_0 = 0.8$ and τ_L = 2-ps, and a plasma length L_p = 10 cm, the gain exponent is $G = 1.7$. This is not large enough to produce strong wake amplification. However, if the laser and plasma conditions are modified slightly, or the interaction is in the three-wave regime, then *G* might be increased by a factor of several so that large wake amplification would be achieved.

Dephasing

Dephasing occurs because the group velocity of the laser that amplifies the wake is lower than *c*. The dephasing distance is

$$L_{ph} \quad = \quad \lambda_0 \left(n_e / n_c \right)^{-3/2}. \tag{5}$$

For $n_e = 10^{16}$ cm^{-3} and a CO_2 laser, L_{ph} = 34 cm. In order to both limit dephasing and avoid electron bunch defocusing, the plasma length should be less than half L_{ph}, which is 17 cm for this example. The target plasma length L_p = 10 cm satisfies this condition.

Capillary plasma

Plasmas have been generated in capillary discharges in a series of experiments at the Naval Research Laboratory [7]. The capillary channels are a few hundred microns in diameter and several centimeters in length. This technique provides a hollow density profile structure. Efficient laser channeling has been demonstrated. Recent experiments achieved densities ~10^{16} – 10^{17} and electrons temperatures ~5 – 6 eV [8]. Capillary discharge plasma equipment has been installed on the ATF and used to demonstrate CO_2 laser channeling [5].

NUMERICAL MODELING OF LWFA AT ATF-CONDITIONS

Numerical studies are needed to account for effects that are missed by the simple analytic estimates in the previous section. The simulations can include realistic factors such as (1) finite laser pulse length, (2) realistic laser time history, (3) radial structure of the ambient plasma, and (4) evolution of the laser pulse envelope (radial and longitudinal). The code used for the modeling was developed by Andreev and associates [9]. The model assumptions used in the computations are shown in Tab. II. The laser pulse is Gaussian both in time and radius. The plasma has a parabolic density profile in the radial direction and the density at $r = R$ is double that on axis. For this example the Rayleigh length is 0.57 cm.

Figure 1 shows the modulation of the laser pulse that has set in after propagating a distance of 5.2 cm through the plasma. The pulse dynamics indicates the presence of self-focusing (mainly ponderomotive) and pulse shortening. A significant modulation of the trailing edge of the pulse (30-50%) is observed after 5 cm of propagation.

TABLE II. Simulation of Long-Laser-Wavelength LWFA.

	Parameter	Value
Laser	Pulse duration, τ_L	2 ps
	Peak power	2.5 TW
	Pulse energy	5 J
	90% power radius	144 μm
	Normalized field, a_0	0.8
Plasma	Density on axis	1.2×10^{16} cm^{-3}
	Radius, R	191 μm

The plasma electron density is shown in Fig. 2. Note the parabolic profile of the ambient density. The modulation in the wake region is ~ 90%.

The *total* wakefield is shown in Fig. 3, which includes the laser field contribution ($a^2/4$). The presence of the latter produces the large first peak. Evidently the wake left behind the laser pulse corresponds to an electric field > 1 GV/m, and is quite regular.

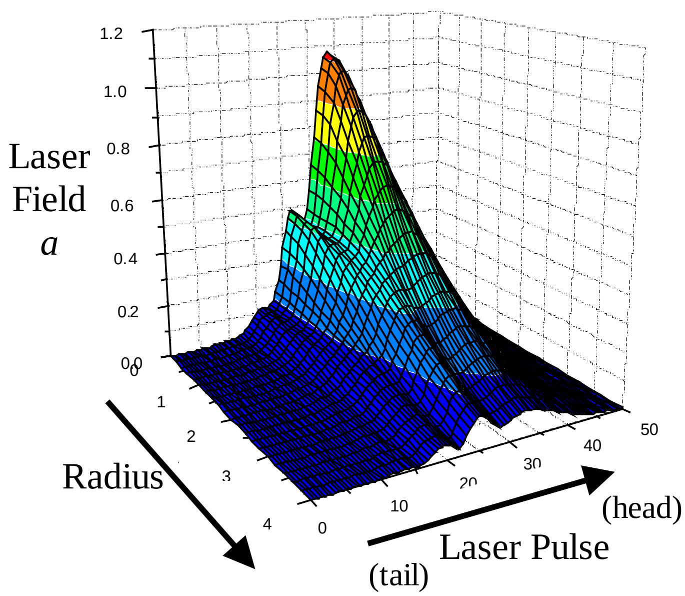

FIGURE 1. Laser field after 5.2 cm propagation.

These preliminary results are promising. The key result is that a strong wake is excited even though the original laser pulse is several times too long for efficient wake excitation by "resonant" LWFA. This is the result of nonlinear pulse shortening due to preferential self-focusing at the maximum of the laser pulse [10] as well as self-phase modulation and group velocity dispersion. These produce a shift in the laser pulse maximum toward the back of the pulse and a sharp drop after the peak [11]. The resulting modification of the laser pulse profile causes the leading and trailing edges to act as if they were a laser pulse of shorter duration. This may have been observed in the experiment by Fritzler [12] where the original laser pulse length was a factor of about 2.5 too long for efficient wake excitation. In short, a much stronger "resonant" LWFA effect is produced than for the unmodified original pulse profile.

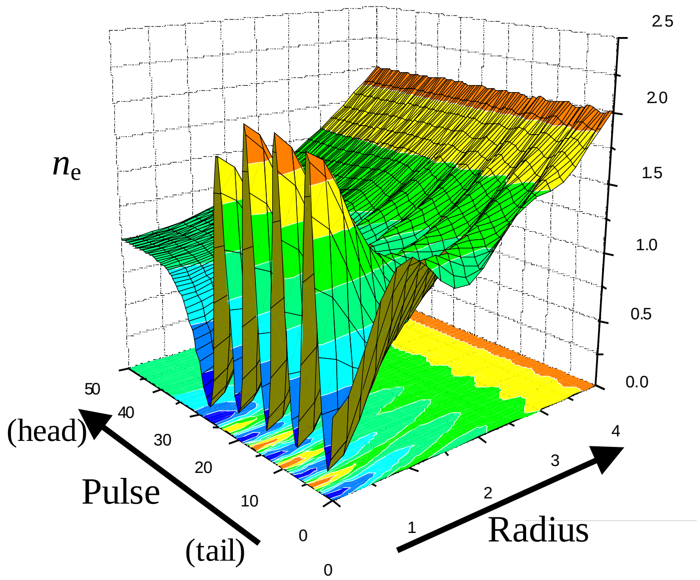

FIGURE 2. Plasma electron density after 5.2 cm propagation.

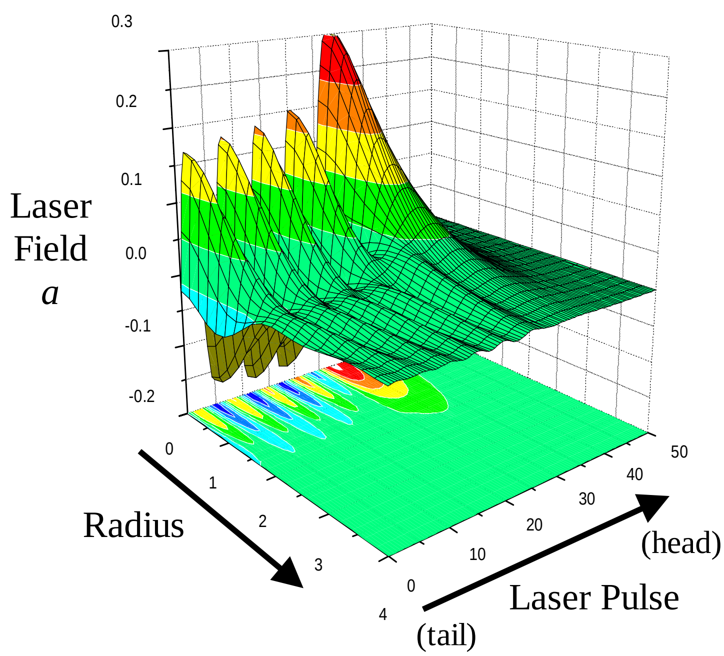

FIGURE 3. Normalized *total* potential (laser + plasma wave) after 5.2 cm propagation.

Issues to be investigated in future studies include the following. (1) Is the wake phase predictable and controllable? (2) Is the wake regular enough to maintain beam quality (emittance, energy spread)? (3) Can an initial wake excited by other means improve the controllability and ultimate strength of the wake?

STIMULATED LWFA CONCEPT

A major issue in LWFA is the controllability and regularity of the wake and the achievement of small energy spread. Here, the insights gained from controlled staging experiments during the STELLA program at the ATF will prove valuable. A possible embodiment for achieving this is the *stimulated LWFA* concept, which involves three steps. (1) A highly-regular "seed" wake of moderate amplitude is generated using a short-bunch *e*-beam bunch or a short pulse laser (~300 fs). (2) A long-wavelength laser pulse follows and amplifies the seed wake. (3) Finally, the witness beam arrives and is accelerated by the strong wake. This is illustrated in Fig. 4.

A key objective is the production of a highly-regular wake. Thus the laser field should be kept *below* the threshold for self-focusing since that produces a highly irregular wake according to simulations [4]. Thus the laser channeling would be achieved by creating a plasma with a density minimum on the axis. Separating the laser-wake-amplification and laser-channeling functions increases controllability.

Stimulated LWFA could be tested on the ATF using existing or planned equipment. The linac would be operated in a double-pulse mode with the shorter first pulse to generate the seed wake. The upgraded (2.5 TW) CO_2 laser would amplify the wake. The laser would be channeled by a capillary-discharge plasma. An important question about stimulated LWFA is whether the wake growth will be aided by the presence of a seed wake while preserving the wakefield phase determined by the seed. Recent results [13, 14] showed that an initial seed makes a large difference in the amplitude of the wake that can be generated.

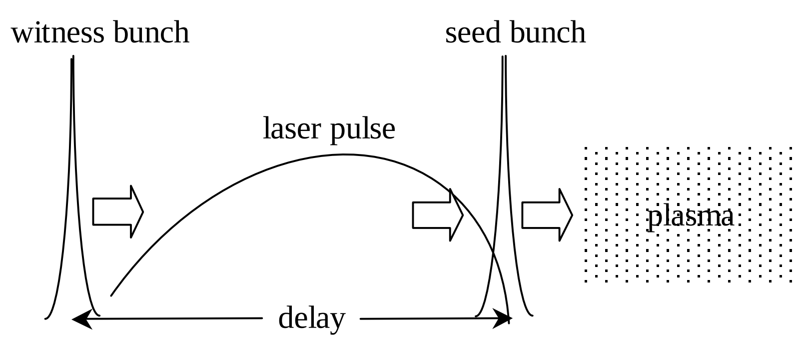

FIGURE 4. Stimulated LWFA.

SUMMARY

The terawatt upgrade of the CO_2 laser at the ATF will enable unique LWFA experiments to be contemplated. These might be the first to demonstrate LWFA at 10.6 μm. Further, they would demonstrate acceleration over an extended interaction length of ~10 cm using capillary discharge plasma for laser channeling. Simulations predict a wake amplitude >1 GV/m for a 2-ps, 2.5-TW laser pulse. A properly phased particle accelerated in this wake over 10 cm would gain >100 MeV energy.

Key issues to be investigated theoretically and numerically in anticipation of an experimental test include the following. (1) Can regular wakes be generated with a controllable phase? (2) How much wake amplification can be achieved? (3) Can the controllability and performance be improved by a seed wake as in the stimulated LWFA concept? Ultimately, a test of staged LWFA can also be contemplated on the ATF. Indeed, staging LWFA is natural extension of the ongoing STELLA program.

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