Laser-driven plasma-based accelerators: Wakefield excitation, channel guiding, and laser triggered particle injection*

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(Received 18 November 1997; accepted 18 February 1998)

Plasma-based accelerators are discussed in which high-power short pulse lasers are the power source, suitably tailored plasma structures provide guiding of the laser beam and support large accelerating gradients, and an optical scheme is used to produce time-synchronized ultrashort electron bunches. From scaling laws laser requirements are obtained for development of compact high-energy accelerators. Simulation results of laser guiding and wakefield excitation in plasma channels, as well as laser-based injection of particles into a plasma wake, are presented. Details of the experimental program at Lawrence Berkeley National Laboratory on laser guiding, laser wakefield-based accelerators, and laser triggered injection are given. [S1070-664X(98)96705-2]

I. INTRODUCTION

As an alternative to rf linear accelerators (linacs), laser-driven plasma-based accelerators† are being studied at various universities and laboratories around the world.‡ In analogy with rf linacs, the plasma-based accelerator needs to consist of an injector, an accelerating structure with longitudinal electric fields that provides mode control for the accelerating fields as well as guiding for the laser, and a suitable laser driver. The most significant differences between laser-driven accelerators and rf accelerators are the two to three orders of magnitude larger longitudinal gradient and equally smaller wavelength of the accelerating fields. Wavelengths on the order of 100 µm are used in laser-driven accelerators, compared to several centimeters in rf linacs. In Sec. II the concept of laser wakefield excitation is discussed and simple scaling laws for the design of laser wakefield experiments are presented. Plasma channels are discussed as means for guiding a high-intensity laser pulse and wake excitation over extended distances. Simulation results from a numerical code modeling the wakefield dynamics in a plasma channel are presented.

Production of electron beams with good pulse-to-pulse energy stability and with low momentum spread using short-wavelength structures places severe constraints on the synchronization between the injected bunch and the wakefield, as well as on the bunch length. These requirements are beyond the state-of-the-art performance of photocathode rf guns. Novel schemes that rely on laser triggered injection of plasma electrons into plasma wakes have recently been proposed.§ These schemes are discussed in Sec. III, including particle tracking simulations of laser injection. In Sec. IV, recent progress will be presented of the experimental laser wakefield accelerator program at Lawrence Berkeley National Laboratory (LBNL). Section V is the conclusion.

II. LASER WAKEFIELD EXCITATION AND GUIDING

The laser driver in a plasma-based accelerator can either consist of a single large-amplitude pulse (so-called “laser wakefield accelerator,” LWFA), a train of pulses with fixed spacing (so-called “plasma beat wave accelerator,” PBWA), or a train of pulses with variable spacing and pulse widths (so-called “resonant laser plasma accelerator,” RLPA). In the case of the LWFA, the laser pulse duration can either be matched to the plasma period (“standard” regime) or be many plasma periods long (“self-modulated regime” or “Raman forward scattering” regime). Scaling laws for wakefield generation using standard LWFA in uniform plasmas and in plasma channels are discussed next.

A. Uniform Plasma

The laser driver will be assumed to have a pulse length comparable to the plasma period, i.e., \( \omega_p \tau = \kappa \pi \). Here \( \tau \) is the laser pulse width [full width at half-maximum (FWHM)], \( \omega_p = (4 \pi n_0 e^2/m)^{1/2} \) is the plasma frequency for an ambient plasma density \( n_0 \), and \( \kappa \) is a scaling factor of order unity.\(^{10} \) Also, \( m \) and \( e \) are the electron rest mass and charge, respectively. The normalized laser strength \( a = E_0 \lambda / \pi m c^2 \), is related to the laser intensity, \( I \), and power \( P \), at a wavelength, \( \lambda \), by

\[
a \approx 8.65 \times 10^{-10} \lambda (\mu m) I^{1/2} (W/cm^2) \\
\approx 6.82 \lambda (\mu m) \sqrt{\frac{P(TW)}{r_{s}(\mu m)^{3}}}.
\]
where $E_0$ is the transverse electric field of the laser, $c$ is the speed of light in vacuum, $r_s$ is the laser spot size ($E_0 \propto e^{-r^2/r_s^2}$) and $I = 2P/(\pi r_s^2)$. The laser pulse will generate a plasma density modulation, $\delta n$, in a uniform plasma with density $n_0$ according to the equation:

$$\mathbf{\nabla} \cdot \mathbf{E} = -4\pi \mathbf{J},$$

where $\mathbf{J} = ne^2c^2\mathbf{E}/m_e^2$.

It is assumed that $r_s$ is much larger than the plasma wavelength, i.e., $k_p^2r_s^2 \gg 1$, that the density modulation is small, $\delta n/n_0 \ll 1$, and that $\alpha \ll 1$. The required plasma density for optimum excitation in a uniform plasma has been calculated for various laser pulse shapes, and is given by

$$n_0 = \frac{\kappa^2 \cdot 3.1 \cdot 10^{21}}{\tau^2 (\text{fs})},$$

where $\kappa$ depends on the laser pulse shape, e.g., $\kappa = 0.75$ for a Gaussian laser pulse. The plasma wavelength $\lambda_p$ corresponding to the matched plasma density can be written as $\lambda_p(\mu m) = 0.69r_0(\text{fs})/\kappa$. For example, the matched density for a 50 fs long Gaussian pulse is approximately $7 \times 10^{17}$ cm$^{-3}$ and the plasma wavelength is about 40 µm. The ratio of plasma density to critical density $n_c$ (the density for which the plasma frequency equals the laser frequency) for this wavelength is only about $4 \times 10^{-4}$, and hence beam refraction issues are expected to play a minimal role in the propagation through the plasma.

The peak longitudinal electric field strength $E_{\text{max}}$ in one dimension (1D) is given by:

$$E_{\text{max}}(\text{GeV/m}) \approx 9.74 \times 10^4 \left( \frac{\lambda_0}{r_s} \right)^2 \frac{\kappa P(\text{TW})}{\tau(\text{fs})},$$

where it is assumed that $\alpha$ and the $\delta n/n_0$ are both much less than unity.

For an accelerating distance limited to the diffraction length $L_{\text{diff}} = \pi Z_R/(\pi r_s)^2/\lambda$, where $Z_R$ is the Rayleigh length of a Gaussian beam (i.e., no guiding) the maximum energy gain of a test particle is:

$$\Delta W_{\text{diff}}(\text{MeV}) = 960 \frac{\kappa \lambda_0(\mu m)}{\tau(\text{fs})} P(\text{TW}) \approx 576 \frac{\lambda_0(\mu m)}{\lambda_p(\mu m)} P(\text{TW}),$$

which is independent of the laser spot size. As an example, for a laser producing 5 TW in 50 fs (i.e., 40 µm plasma wavelength) at a wavelength of 0.8 µm, $\Delta W_{\text{diff}} = 57$ MeV. Also, from Eq. (4), the energy gain is inversely proportion to the number of laser wavelengths per plasma period. Hence, for constant laser power, the same energy gain is obtained in a standard LWFA using a 100 fs long pulse from a $\lambda = 1$ µm laser as for a 1 ps long pulse from a $\lambda = 10$ µm laser. However, the amount of required laser energy will be ten times larger for the 10 µm wavelength laser driver.

Assuming that diffraction of the laser pulse can be overcome by guiding inside a plasma channel, and that the maximum distance of acceleration is limited to the dephasing length, $L_p = \lambda_0^2/\lambda^2$, the maximum energy gain is then:

$$\Delta W_{\text{ch}}(\text{GeV}) \approx 60 \frac{\lambda_0^2}{r_s^2} P(\text{TW}) \approx \frac{I(\text{W/cm}^2)}{n_0(\text{cm}^{-3})}. \quad (5)$$

From Eq. (5), it can be seen that the maximum energy gain is independent of the laser wavelength.

B. Modeling of laser wakefield dynamics in channels

To overcome the limitation on the acceleration distance due to laser beam diffraction, relativistic guiding and plasma channel guiding have been proposed. Self-guiding and channel guiding of laser pulses has been demonstrated experimentally. In the absence of a plasma wave, $\delta n_0 = 0$, the general condition for relativistic guiding (i.e., $r_s = \text{const}$) a long, uniformly uniform pulse in a plasma is $P/P_c \approx 1 - \Delta n/\Delta n_c$. In the limit $\Delta n_p = \delta n_0 = 0$, it can be shown that the relativistic guiding of a long pulse occurs when the laser power satisfies $P \approx P_c$. For short pulses the relativistic correction to the index of refraction is exactly canceled by the $\delta n/n_0$ of the excited plasma wake. On the other hand, in the limits $P/P_c < 1$ and $\alpha^2 < 1$, it can be shown that a parabolic density channel $\Delta n_p = \Delta n r_s^2/r_c^2$ can guide a Gaussian laser pulse, provided that the channel depth satisfies $\Delta n \geq \Delta n_c$, where $\Delta n_c = (\pi r_s^2)^{-1}$ is the critical depth, and $r_e = e^2/m_ec^2$ is the classical electron radius.

Previous theoretical studies of plasma wakes in channels have considered either step function transverse density profiles, for which there is an exact expression for the wake, or, alternatively, parabolic profiles. The drive pulse propagation theory is simpler for a parabolic profile, but until now the wake calculation has been made, assuming the density gradient is weak. Hollow channels, while perhaps difficult to realize in the laboratory, have many desirable properties for acceleration, such as (up to order $\alpha^2/\alpha^2$) a transversely uniform accelerating field and linear focusing forces. Plasma channel profile control is therefore a key issue: both the transverse profile of the wakefield structure left by the laser pulse and the damping of the wakefields in time are indeed determined by the shape of the plasma channel. Next, we discuss theoretical efforts on modeling the excitation of plasma wakes in channels, and in Sec. IV we discuss experimental progress on characterizing plasma channel profiles.

As part of an ongoing program of developing efficient numerical tools for designing plasma-based accelerators, development is underway of a code for simulating wakefield generation and laser propagation in a plasma channel, where the plasma electrons are modeled as a cold, nonrelativistic fluid. Although fluid codes cannot account for trapped particles or wave breaking as well as other purely kinetic effects, they have the advantage that one has control over the detailed physics involved.

In the fluid code the plasma is described by a density field, $n$, and velocity field, $\mathbf{v}$. Newton’s second law and conservation of mass yield the equations

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = \frac{q}{m} \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right), \quad \frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{v}) = 0, \quad (6)$$

where the electric and magnetic fields are coupled to the plasma through Maxwell’s equations:
where $n_i$ is the fixed background ion density. These equations are linearized about an equilibrium electron density $n_0$. Note that although nonuniform equilibria are hydrodynamically unstable, experiments operate on a much shorter time scale than hydrodynamic instability. The linear system is then further simplified by transforming to a frame comoving with the laser pulse and assuming the system is nonevolving, i.e., all quantities depend only upon $\xi = z - ct$ and $\mathbf{r}_x$. By adopting slab geometry, we reduce this to a one-dimensional (1D) time-dependent problem, with $\xi$ taking the role of the time-like variable. Under these assumptions, the equations describing the wakefields ($\mathbf{E}$ and $\mathbf{B}$) in the region behind the laser pulse are given by

\begin{align}
\nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} &= 0, \\
\nabla \cdot \mathbf{B} &= \frac{4\pi}{c} q n v, \\
\n\nabla \cdot \mathbf{E} &= 4\pi q (n - n_i),
\end{align}

where $\mathbf{v}$ is the fluid velocity and $\mathbf{B}$ is the magnetic field. These equations present a boundary-value problem in $x$ (the remaining transverse dimension) and an initial-value problem in $\xi$ (the distance from the laser pulse). While our preliminary code is based on a reduced set of fluid equations [Eq. (8)], we have obtained some interesting results that illustrate the utility of fluid models. In particular, for nonuniform equilibrium plasma density (for example, see Fig. 1), we observe dissipation of the wakefields and a related fine-scale spatial structure in the electric and magnetic fields. The dynamics of a wakefield in a nonuniform plasma are shown in Fig. 2. Initially, as seen in Fig. 3, the various plasma fields...
and densities are slowly varying in space with scale lengths comparable to the scale of the equilibrium density profile. As this system evolves, the large longitudinal electric field dissipates. The energy associated with this field is transferred to both the transverse electric field and the transverse velocity of the electrons in the plasma walls. In the region where the equilibrium density is varying, the fields, as well as the transverse current density and the perturbed plasma density, develop fine-scale spatial structure with significant amplitude. For example, at \( \frac{\xi}{\omega_p} \approx 30 \), the longitudinal electric field has dissipated to approximately 30% of its initial value and a fine spatial structure, with wave number \( k \approx 30 k_p \), is clearly evident (see Fig. 4). These results are in close agreement with a Laplace transform analysis, which yields the damping rate and oscillation frequency of the channel mode. The transverse current density develops an increasing amount of shear, \( \nabla v \), confined to the region where \( d \omega_p / dx \neq 0 \), i.e., the channel walls. The net current in the wall is significantly reduced due to this highly sheared velocity (and current) distribution, leading to a much reduced longitudinal field on axis. Although the present code does not include the nonlinear term \( \mathbf{v} \cdot \nabla \mathbf{v} \), the qualitative aspect of the field distribution is believed to be accurately modeled, for sufficiently small initial fields (i.e., \( a \ll 1 \)). Modifications to this behavior due to nonlinear effects will be reported in a future paper.

Recent work has also concentrated on understanding how the driving laser pulse evolves as it propagates through a uniform plasma and through a channel. From simple one-dimensional scaling laws, laser wavelength reddening and pulse length shortening are qualitatively described. One-dimensional self-consistent equations that provide a detailed description of the laser pulse evolution for the case of propagation in a uniform plasma, have been extended to treat the case of laser pulse propagation in a hollow channel. The
coupling between the plasma and the laser pulse was calculated using energy conservation and a simple method for inferring the plasma wake characteristics from measurements of changes in phase and amplitude of the driving laser pulse was obtained. The implications of the changes in laser pulse properties on pump depletion, and hence efficiency, of laser wakefield accelerators are being studied theoretically.

III. LASER INJECTION

As discussed in the Sec. I, the generation of electron bunches with stable energy and low momentum spread using plasma structures with a characteristic scale length on the order of a few tens of μm requires femtosecond electron bunches to be generated with femtosecond synchronization with respect to the plasma wake. All-optical methods have been proposed for injection into a standard LWFA using a first laser pulse to generate the wakefield (i.e., plasma oscillation) and a second to locally dephase electrons that then can get trapped in the plasma wake. Recently, a scheme has been proposed that relies on the use of three collinear laser pulses: an intense laser pulse (denoted by subscript 0) that generates a large wakefield (>20 GeV/m), and two counterpropagating injection pulses (denoted by subscript 1 and 2 for forward and backward, respectively). This "colliding" laser pulse scheme for laser triggered injection of electrons is discussed next. The frequency, wave number, and normalized intensity of the three pulses are denoted by ω₁, k₁, and a₁ (i = 0, 1, 2), respectively. Figure 5 shows the profiles of the pump laser a₀, the wake potential φ, and the forward a₁ injection pulse, all of which are stationary in the z = 0 plane, and the backward injection pulse a₂ that moves to the left, where vₚ₀ ≈ c is the phase velocity of the wake. Furthermore, ω₁ = ω₀ − Δω, ω₂ = ω₀, and ω₀ ≫ Δω ≫ ωₚ are assumed, such that k₂ = −k₀ and k₁ ≈ k₀. When the injection pulses collide (some distance behind the pump) in the plasma wake of the pump laser, they generate a slow phase velocity ponderomotive beat wave. This beat wave can cause electrons, undergoing a plasma oscillation caused by a₀, to acquire a momentum and phase change sufficient for trapping.

In the 1-D limit (kₚrₚ ≫ 1), the equations of motion of an electron in the longitudinal, electrostatic plasma wake \[ \psi(t) = \phi_0 \cos(\phi) \] and the electromagnetic fields of the colliding laser pulses \( \vec{a} = \vec{a}_1 [\vec{x} \sin(\phi_1 + \vec{y} \cos(\phi_1))] \) is given by

\[
\frac{d\vec{z}}{dt} = \beta c, \quad \frac{d(\gamma \beta \vec{v})}{dt} = \frac{\partial \vec{\phi}}{\partial \vec{z}} - \frac{1}{2 \gamma} \frac{\partial a^2}{\partial \vec{z}},
\]

\[
\frac{d\gamma}{dt} = \beta \frac{\partial \vec{v}}{\partial \vec{z}} + \frac{1}{2 \gamma} \frac{\partial a^2}{\partial \vec{v}}.
\]

Here \( a^2 = a_1^2 + a_2^2 + 2a_1a_2 \cos(\phi_1 - \phi_2) \) is the ponderomotive potential produced by the beating of the two colliding pulses \( \phi_1 = k_1 (z - \beta \phi_1 c t) + \phi_1 \) the phase of the electromagnetic field with phase velocity \( \beta_1 c = \omega_1 / k_1 \). Temporal and spatial coordinates have been normalized with respect to \( \omega_0 \) and \( k_p \), respectively, and potentials have been normalized with respect to the rest mass energy of the electron. Also, the pump and counterpropagating laser pulses are assumed to have opposite polarization, such that \( a_0 = a_2 = 0 \).

Equation (9) is solved numerically and the particles are loaded with a uniform distribution in phase, where \( \psi_j \) is the phase of the jth electron on an untrapped wake orbit, with

\[
\beta_{ij} = \beta_0 \left[ 1 + \phi(\psi_j) \right] \sqrt{\beta_0^2 - \left[ 1 + \phi(\psi_j) \right]^2}.
\]

Here \( \beta_{ij} \) is chosen such that the electrons are at rest prior to the wake generation, i.e., \( 1 = \gamma j (1 - \beta_0 \beta_j) - \phi(\psi_j) \) and \( \beta_0 = v_p c / c \). As an example, Fig. 6 shows the orbit in phase space \( (\gamma \beta, \phi) \) of a single particle in the plasma wake with (solid curve) and without (dashed curve) the colliding pulses. The simulation parameters were \( \phi = 0.7, a_1 = a_2 = 0.5, \lambda_p = 40 \mu m, \lambda_0 = \lambda_2 = 0.8 \mu m, \lambda_1 = 0.9 \mu m \), and laser pulse lengths \( L_1 = L_2 = 10 \mu m \). As can be seen from Fig. 6, the effect of the beating of the colliding pulses is to cause a momentum and phase shift across the plasma wake separatrix from an untrapped to a trapped orbit. Figures 7(a)–7(d) show the electron energy versus the phase in the wake (dots), before, during, and after the laser pulses collide, with the separatrix that distinguishes the trapped and untrapped regions superimposed (a dashed line).

Particle tracking simulations in 1D⁴ and 3D²⁶ indicate that the production of high-current electron bunches as short...
as 3 fs, with a mean energy on the order of 25 MeV and a normalized energy spread of 0.3% are possible after an acceleration distance of 1.5 mm, using injection laser pulse intensities on the order of $10^{17}$ W/cm$^2$. The number of trapped electrons in a plasma with a density of $7 \times 10^{17}$ cm$^{-3}$ is on the order of $10^6$, with a normalized emit-tance on the order of 1 mm mrad. Detailed parametric studies of the beam dynamics in one and three dimensions are underway to completely characterize the longitudinal and transverse phase space properties of the trapped electron bunches.26

IV. LWFA LASER SYSTEM AND CHANNEL INTERFEROMETRY RESULTS

As discussed in Sec. II, the standard LWFA scheme requires a laser system that is capable of generating high peak power (TW) short (<100 fs) laser pulses with a duration matched to the plasma period. Second, overcoming diffraction of the laser pulse by relying on channel guiding, i.e., increasing the acceleration distance, requires a multi-ps long laser pulse for plasma channel generation.19 Third, time-synchronized pulses are needed for diagnosing channel formation and for probing wakefield characteristics. And finally, a laser triggered injection scheme relies on near perfect synchronization between the drive laser pulse and the two colliding laser pulses. Furthermore, the production of an electron beam with an average beam current comparable to standard rf technology demands all these laser pulses to be generated at a high repetition rate (10 Hz or more). Next, we will discuss a multiterawatt laser system that is being built at Lawrence Berkeley National Laboratory (LBNL), with the unique design feature that such perfectly time-synchronized pulses with different time structure and energy are produced from a single master oscillator laser. We also present recent results on time-resolved studies of laser-produced plasma channels. As discussed in Sec. II, knowledge of the plasma channel transverse profile is essential in determining the characteristics of the wakefield profiles.

A. Laser system

The laser system starts with a Kerr lens mode locked Ti:Al$_2$O$_3$ oscillator, lasing at about 0.8 μm ("red" beam), which produces a 90 MHz train of pulses with an average power of about 0.25 W. The spectral bandwidth (and hence pulse length) is controllable from about 10–60 nm with an intracavity slit. The oscillator pulses are first stretched by a single grating (1200 g/mm groove density) all-reflective optics stretcher to a length of up to 300 ps, controllable through the bandwidth of the injected oscillator pulses. The stretched pulses are amplified in a regenerative amplifier, which is pumped with a 1 kHz intracavity doubled Nd:YLF laser. The output of the amplifier is split into two beams, with one beam (about 5% energy) being sent to the built in compressor and the remaining 1.2–1.5 mJ sent to a two-pass preamplifier. The compressed beam is frequency doubled (400 nm "blue" beam) and is used as the probe beam for the plasma interferometry diagnostic, which will be described below.

The three-pass preamplifier Ti:Al$_2$O$_3$ crystal (1 cm diam, 1.5 cm long), pumped by typically 380 mJ of 532 nm radiation from a commercial Q-switched, frequency doubled Nd:YAG laser operating at 10 Hz, produces about 45–50 mJ per pulse. The pump fluence in the preamplifier is about 3.2 J/cm$^2$. The pulses are then amplified in a 2+2 pass main amplifier. The main amplifier crystal (1.5 cm diam, 1.5 cm long) is pumped from both sides with 9 mm beams containing up to 1 J energy (per side) in a 7–8 ns long pulse at 532 nm. The 532 nm radiation is produced by a frequency doubled Nd:YAG laser system that consists of an oscillator–amplifier Q-switched laser that generates a 1.2 J flat top mode that is relay imaged on the input of two amplifier arms, each having two amplifier heads. The $>2$ J output per arm is...
frequency doubled and relay imaged onto the Ti:Al₂O₃ to maintain a flat top pump profile. At the present time, using a total of 1.8 J pump beam, we have produced about 400 mJ after passing the amplifier crystal twice. About 60% of the pulse energy is directed toward a single grating, folded vacuum compressor to produce about a 100–120 mJ pulse in 70–75 fs measured using a frequency-resolved optical grating system FROG. This short pulse will be used for wake excitation experiments. Calculations indicate that gain saturation in the Ti:Al₂O₃ crystal after two passes is expected to be minimal and therefore cause no significant spectral distortion. The remaining pulse energy double passes the main amplifier again, resulting in an energy of 400–500 mJ. This long pulse is used for the production of channels. Optical delay lines have been implemented to ensure proper timing between the terawatt pulse, the long pulse and the blue probe pulse.

B. Interferometry of laser-produced plasma channels

The measurement of density profiles in laser-produced plasma channels through interferometry has shown that the required density profile can indeed be achieved for guiding of laser pulses over distances long compared to the Rayleigh length. Here, we report recent results on plasma production and the interferometric measurement of plasma density profiles using the compressed and uncompressed regenerative amplifier and preamplifier output. The goal of these experiments is to gain a detailed understanding of the channel formation and its control through the laser pulse parameters.

A Mach–Zehnder-type interferometer with a measured spatial resolution of 4 μm was used to measure the line-integrated laser-produced plasma density. This interferometer measures the relative spatial phase shift between two blue (400 nm) 50 fs pulses: one propagating through plasma and the other one propagating through air. Figure 8 shows a two-dimensional interferogram and phase shift profile obtained by propagating the probe beam through a plasma produced with an uncompressed pulse (10 mJ energy in 150 ps, 10¹⁴ W/cm²).

![Two-dimensional interferogram and phase shift profile obtained by propagating a 400 nm wavelength probe beam transversely through a plasma.](image)

**FIG. 8.** Two-dimensional interferogram and phase shift profile obtained by propagating a 400 nm wavelength probe beam transversely through a plasma, immediately after (a), (b) and 500 ps after ionization (c), (d). The plasma was produced in a static fill of N₂ by a laser pulse (10 mJ in 150 ps, 10¹⁴ W/cm²).

![Plasma density profiles obtained through Abel inversion of the line profile through the phase shift contours [Figs. 8(b), 8(d)] at the positions marked by the arrows.](image)

**FIG. 9.** (a) Plasma density profiles obtained through Abel inversion of the line profile through the phase shift contours [Figs. 8(b), 8(d)] at the positions marked by the arrows. (b) Plasma size, obtained from laser interferograms, versus the probe beam delay time. The plasma was produced by focusing a laser beam (10 mJ energy in 150 ps) into a static fill of N₂ at a pressure of 380 Torr. The data is in good agreement with a t¹/₂ dependence (solid curve), as expected from theory.

By delaying the blue beam in time with the ionizing beam, plasma expansion, and channel formation was observed, as seen in Fig. 9(a). From the rate of expansion [Fig. 9(b)] we have inferred an ion acoustic speed of 6 × 10⁸ cm/s. We find that the average ionization degree is about 3, resulting in a plasma temperature of about 65 eV. The expansion is found to evolve as t¹/₂, as expected from theory.
discussion in Sec. IV B, such a channel is capable of guiding a laser pulse. Integration of the obtained three-dimensional density profiles indicates that there is an increase of about 10%–20% of the total number of electrons, in agreement with hydrodynamic simulations that indicate continuing collisional ionization as the shock wave expands outward. Channel formation over longer lengths (0.5 cm–1 cm) as a function of laser parameters is currently being studied in a gasjet to avoid ionization induced refraction, associated with the use of a static fill. These experiments aim at the optimization of the channel shape through control of the amount of laser heat deposition (i.e., inverse bremsstrahlung), with the goal of guiding the high-intensity ultrashort pulses in channels and the excitation of plasma wakes with properties suitable for acceleration of particles. Experimentally measured profiles will be used to calculate expected wakefield profiles as discussed in Sec. II.

V. CONCLUSION

Scaling laws have been presented for designing laser guiding and wakefield excitation experiments. From a 1-D analysis, energy gain in a standard LWFA without channel guiding is shown to be proportional to the laser power and the ratio of laser to plasma wavelengths, i.e., inversely proportional to the number of laser periods per plasma period. Through the dependence on laser energy, however, shorter-wavelength lasers, capable of producing ultrashort pulses and hence ultrahigh peak powers, are favored. In the case of a channel guided LWFA, the energy gain is proportional to the ratio of laser intensity and plasma density, which is independent of the laser wavelength.

Simulation results from a fluid-based code on the laser wake dynamics in channels have been presented. Such fluid codes have the advantage over particle-in-cell (PIC) codes through the control of the detailed physics used in the model, and through the computational speed, which is a direct aid in optimization of experiments, with quick turnaround time. For nonuniform equilibrium plasma density, we observe dissipation of the wakefields and a related fine-scale spatial structure in the electric and magnetic fields.

The effect of the plasma on the laser pulse evolution in a uniform plasma and a channel has also been studied. From simple one-dimensional scaling laws, laser wavelength redening and pulse length shortening have been qualitatively described.

We have also discussed a novel scheme for particle injection into plasma wakes based on a colliding laser pulse scheme. Simulations indicate that the physical mechanism for the particle trapping is a momentum and phase kick caused by the ponderomotive beat wave potential of the two counterpropagating, colliding laser pulses. Particle tracking simulations in one dimension further indicate that production of high-current electron bunches as short as 3 fs, with a mean energy on the order of 25 MeV and a normalized energy spread of 0.3% are possible after an acceleration distance of 1.5 mm, using injection laser pulse intensities on the order of 10^{17} W/cm².

Finally, progress on the experimental program at LBNL has been presented. A multiterawatt laser system, which is capable of producing perfectly time-synchronized laser pulses with different pulse lengths and energies is nearing completion. Time-resolved interferometric studies on plasma channel production for the guiding of high-intensity laser pulses are underway. Laser ionization and heating of plasmas has been observed, leading to plasma density channels in laser-produced plasmas. The present experiments are concentrating on control of the plasma channel properties in laser-ionized gas jets, through laser pulse length and energy and on the propagation of laser pulses with intensities on the order of 10^{18} W/cm². Experimentally measured plasma channel profiles will be used in the fluid codes to predict wakefield profiles excited by propagating a short intense laser through the channel.

Last, laser injection using the colliding laser pulse scheme will be studied experimentally. A second TiAl₂O₃ amplifier chain is planned to increase the available laser power to the 10 TW level, and a double focusing magnetic spectrometer and femtosecond electron bunch measuring system are being designed for measuring the energy spectrum and electron bunch length, respectively.

ACKNOWLEDGMENTS

We would like to acknowledge useful discussions with Max Zolotorev on the laser injection scheme and beam diagnostics and the technical contributions from Leon Archambault and Jim Dougherty. We would also like to acknowledge Earl Marmar for making the Abel inversion algorithm available, and assistance on laser safety from K. Barat.

This work is supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Dept. of Energy under Contract No. DE-AC-03-76SF0098.


The expression for Abel inversion involves an integral of the first derivative of the measured line-integrated quantity, phase shift in this case. The method used in this paper relies on second derivative smoothing of the experimental data: depending on a variable parameter, the algorithm averages neighboring points to a larger or lesser degree, thereby preventing high-frequency, point-to-point phase fluctuations from distorting the result.


P. Volfbeiyn and W. P. Leemans, in preparation.