

RELATIVISTICALLY STRONG CO<sub>2</sub> LASER DRIVER  
FOR PLASMA-CHANNELED PARTICLE ACCELERATION \*

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Abstract

Long-wavelength, short-duration laser pulses are desirable for plasma wakefield particle acceleration and plasma waveguiding. The first picosecond terawatt CO<sub>2</sub> laser is under development to test laser-driven electron acceleration schemes.

I. Introduction

High-power CO<sub>2</sub> lasers are traditionally attractive for strong-field physics applications. Such interest is based upon the ability to build fairly economical large-aperture, large-volume devices with high-energy output and high repetition rates. The list of scientific applications of pulsed CO<sub>2</sub> lasers includes: plasma physics, laser chemistry, far-IR laser pumping, study of nonlinear effects in semiconductors, lidars, etc. Laser-driven particle accelerators is another emerging application area for high-power lasers that may benefit from long-wavelength CO<sub>2</sub> radiation.

In general, particle acceleration by a fast-oscillating electromagnetic field becomes possible when a relativistic particle moves in synchronism with the phase of the driving field. The relatively long wavelength of a CO<sub>2</sub> laser ( $\lambda=10.6 \mu\text{m}$ ) helps to meet this requirement.

Utilizing this feature, a 10-GW table-top 100-ps CO<sub>2</sub> laser<sup>1,2</sup> is used at the Brookhaven Accelerator Test Facility (ATF)<sup>3</sup> to test several laser acceleration schemes. They include: Inverse Cherenkov Accelerator (ICA),<sup>4,6</sup> Inverse Free Electron Laser (IFEL) Accelerator,<sup>7,8</sup> and, in the future, Grating Linac.<sup>9,10</sup> These schemes are related to far-field and near-field laser acceleration methods.<sup>11</sup> Electron acceleration to several MeV has been demonstrated by the ICA and IFEL techniques with a possible upscale to 100 MeV, provided at least 200 GW laser beam is available.<sup>5,8,11</sup>

Another specific of the long-wavelength CO<sub>2</sub> laser radiation is based on a quadratic dependence ( $\propto \lambda^2$ ) of the ponderomotive potential - energy of oscillatory motion acquired by the electron from the electromagnetic wave. The ponderomotive potential is the key parameter for the processes related to the electron oscillation: relativistic self-focusing, ionization, plasma wave excitation, etc. That is why high peak-power CO<sub>2</sub> lasers are especially attractive for laser acceleration in a plasma. This group of acceleration methods is based on coupling of laser radiation into plasma waves and acceleration of trapped electrons by the electrostatic field formed by periodic electron-ion charge separation.

In two twin Laser Beat Wave Accelerator (LBWA) experiments at UCLA<sup>12</sup> and Chalk River Laboratories<sup>13</sup>, 200 GW, 300 ps CO<sub>2</sub> lasers, frequency-modulated with a period of the plasma wave, produced 3-6 GeV/m accelerating field over a 0.5-1 cm distance resulting in ~30 MeV electron acceleration.

The efficiency of plasma acceleration schemes, that, in addition to LBWA, include Laser Wakefield Accelerator (LWFA) and their modifications, is greatly enhanced by further laser power increase and pulse shortening. Recently demonstrated 44 MeV LWF electron acceleration over the 0.5 mm interaction distance (equivalent to 100 GeV/m accelerating field) with a multi-terawatt picosecond mode-locked solid state laser gives another promise to further advancement of the plasma-based concepts towards the next-generation laser-driven particle accelerators.<sup>14</sup>

So far, such a combination of multi-terawatt peak power and a short picosecond pulse duration, desirable for the LWFA scheme, was never achieved with CO<sub>2</sub> lasers. Because of the relatively narrow rotational structure typical for molecular gas spectra, picosecond pulse formation via mode-locking technique has not been as successfully obtained with CO<sub>2</sub> lasers as with solid state lasers, which have wide crystal-host broadening of the individual ion spectral lines. However, alternative ways to produce CO<sub>2</sub> pulses with picosecond time scales have been developed. One of them is semiconductor switching based on modulating the reflective and transmissive properties of a semiconductor IR window by optically controlling the free-carrier charge density. Subpicosecond CO<sub>2</sub> pulses have been gated by this method.<sup>15</sup> However, the potential for high-peak-power extraction in a short single picosecond pulse from a high-volume CO<sub>2</sub> amplifier has not been realized so far. This approach is pursued at the ATF where a several-terawatt picosecond CO<sub>2</sub> laser is under construction.

A major limitation to scaling the plasma-based laser accelerator schemes is the short interaction region in which the high laser intensity may be maintained. The length of this region is defined by the Rayleigh distance measured from the focal point to the point where the laser beam expands two times in cross-sectional area. For typical conditions of plasma acceleration experiments, this distance is limited to a few millimeters or even less than a millimeter. This restricts the energy gain attainable

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in a single-stage particle accelerator driven by a terawatt-class laser to  $\sim 100$  MeV. To reach the next milestone of a 1 GeV acceleration, far more powerful lasers would be needed. However, extremely high laser power (e.g., petawatt) with  $\sim 1$  TV/cm transverse electric fields may be more destructive than productive for plasma-based accelerators due to ponderomotive blow out of the plasma from the Rayleigh region.

A possible way to increase the net acceleration without scaling up the drive laser power is optical guiding. Optical guiding options, applicable to laser-driven electron accelerators, include: self-focusing due to thermal, nonlinear, ponderomotive, and relativistic effects,<sup>16,17</sup> and preformed plasma density channels<sup>17,18</sup>. Extended cylindrical plasma channels produced under gas breakdown by axicon-focused laser beams<sup>19,20</sup> may be used for channeling laser beams over many Rayleigh lengths.

Among known plasma-based laser acceleration techniques, Self-Modulated (SM) LWFA looks now the most promising. This method requires a so called "relativistically strong" laser beam that satisfies conditions for relativistic self-focusing. In the present paper, we show how this scheme may benefit from using a channeled CO<sub>2</sub> laser as a driver.

In Section II, we describe an approach to a relatively compact CO<sub>2</sub> laser system designed to deliver 4 TW, 3-5 ps pulses.

Plasma channels produced by axicon-focused laser beams are briefly discussed in Section III.

In Section IV, we consider potential advantages of using a relativistically strong CO<sub>2</sub> laser as a SMLWFA driver. Recent simulations<sup>21</sup> demonstrate a possibility of accelerating electrons from 50 MeV to the 500 MeV level over a 4 cm distance using 4 TW CO<sub>2</sub> laser pulses propagating inside a preformed channel in underdense plasma.

## II. Terawatt CO<sub>2</sub> Laser Project

The projected terawatt CO<sub>2</sub> laser system is the upgrade version of the presently operational 10-GW ATF CO<sub>2</sub> laser system<sup>2,3</sup>. As long as a number of basic principles and elements of the present system will be preserved after the upgrade, it would be relevant to give their brief overview.

The ATF CO<sub>2</sub> laser system includes: a hybrid TEA oscillator, picosecond semiconductor switch, and a UV-preionized multipass TE amplifier.

In the laser oscillator, a diffraction grating tunes the laser wavelength stepwise between the individual rotational lines in the gain spectrum of the CO<sub>2</sub> molecules, which are vibrationally excited in the electric discharge. In addition to the 1-atm discharge-cell, the oscillator also includes an auxiliary low-pressure discharge cell. The narrow spectral line of the low-pressure discharge selects the particular longitudinal eigenmode to build up inside the laser cavity. Piezo-tuning of the cavity length matches a mode spectral position to the gain peak. The output single-mode laser pulse has a smooth envelope, free from the stochastic mode-beat spikes otherwise typical for free-running TEA CO<sub>2</sub> lasers.

The semiconductor switching method is used to slice a 100-ns oscillator pulse to the desired picosecond width. A short-wavelength picosecond laser pulse with a photon energy above the band gap of the semiconductor creates, upon absorption, a highly reflective electron-hole plasma in the surface layer of a semiconductor, such as germanium, which is normally transparent to 10- $\mu$ m radiation. A 10-ps Nd:YAG laser, that serves as a photocathode driver for the ATF linac, also supplies a 1.06- $\mu$ m pulse for slicing. Using the same initiator for the linac and for the CO<sub>2</sub> pulse slicing ensures the desired picosecond synchronization of the electron bunch and laser pulse at their interaction region.

To reach a power level needed for laser accelerator studies, the switched picosecond pulse is transmitted through the 8-pass CO<sub>2</sub> amplifier that features a 120-cm long, 3-atm, UV-preionized, transverse electrical discharge energized by a 150-kV pulse. The limited spectral bandwidth of the amplifier defines  $\sim 100$  ps minimum duration of the output laser pulse. Thus, at the amplifier output energy of 1 J, corresponding peak power is  $\sim 10$  GW.

To meet demands of advanced accelerators, the ATF is developing a modified CO<sub>2</sub> laser system of a terawatt power level. It would not be an intelligent way to increase the laser power just via the output energy boost as has been done previously. First, it drives upward the physical dimensions and energy supplies to the system. Second, it increases energy fluence through the optics which is the limiting factor to high power extraction from the amplifier and delivery to the experiment. Hence, laser pulse shortening would be necessary. A short laser pulse, compatible with a few picosecond electron bunch from a photocathode e-gun of the ATF linac, is also desirable for the efficient plasma wave generation in the laser accelerator.

How short may be a pulse produced from the CO<sub>2</sub> amplifier? We already mentioned the bandwidth limitations to laser pulse shortening. Indeed, when a short laser pulse propagates in a molecular medium with a periodically modulated rotational spectrum, the nonuniform spectral gain modifies the spectral envelope of the pulse. The intensity envelope, related to the pulse spectrum by the inverse Fourier transform, will be correspondingly reshaped. When the initial laser pulse duration is comparable to or shorter than characteristic time-constants of the medium, the pulse may lengthen or even split into a train of pulses. The period in this train corresponds to a frequency interval between the centers of rotational lines, which is 18 ps for the 10P CO<sub>2</sub> band.

Smoothing of the molecular spectrum via pressure broadening helps to minimize the laser pulse distortions. Numerical calculations demonstrate that 30 ps pulses can propagate in a 10-atm amplifier without appreciable distortions.

An alternative way to achieve gain smoothing is to reduce the spectrum modulation period approximately 4-times using an isotopic gas mixture. Computer modeling shows that pulses as short as 3-ps may be amplified in a 5-atm multi-isotope amplifier.

The design concept for the CO<sub>2</sub> laser upgrade presumes slicing and then amplification of a short (close to 3 ps) laser pulse. We also expand the discharge cross-section, thus allowing a high energy extraction through the large-aperture output window. Both pulse shortening and energy increase should permit an increase of the peak power from several GW to several TW level. Fig.1 presents the principal configuration for the modified CO<sub>2</sub> laser system. The presently operational oscillator and semiconductor switch will supply a picosecond seed pulse into a regenerative preamplifier which will share a portion of the active discharge region in a large-aperture multi-isotope amplifier. Essential for the amplifier design is the use of an x-ray preionizer and 1 MV pulse to energize the uniform discharge of a 10 liter volume under high pressure. Four additional passes, after the regenerative amplifier with beam expansion to ~60 cm<sup>2</sup>, will boost the output power to the 4 TW level in a 3-5 ps pulse.

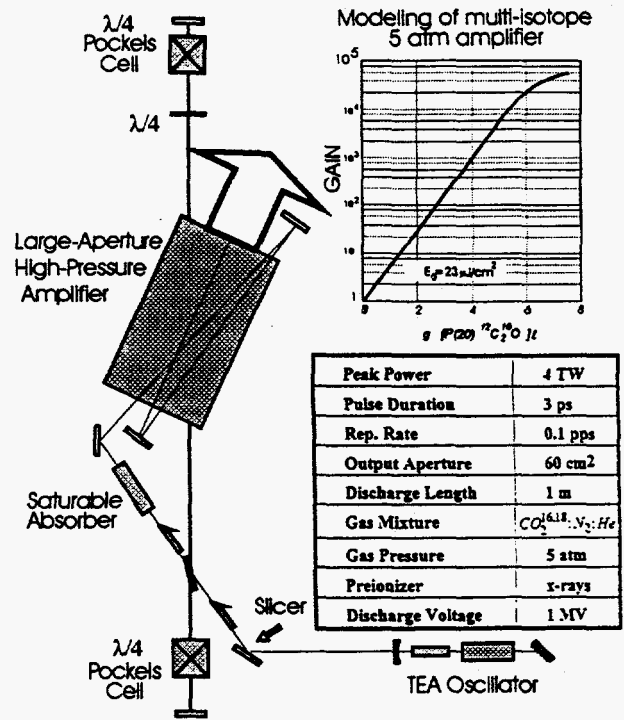


Fig.1 Approach to the terawatt CO<sub>2</sub> laser system design

### III. Plasma Channeling Methods

High intensity required to achieve strong accelerating field in a plasma accelerator presumes sharp laser focusing. However, the short Rayleigh length,

$$z_0 = \pi w_0^2 / \lambda, \quad (1)$$

where  $w_0$  is the focal waist radius and  $\lambda$  is the laser wavelength, limits the effective interaction length and, thus, the net acceleration. Waveguiding may help to maintain a high laser intensity over the appreciably long distance.

Let us characterize first the conditions for waveguiding. Consider a collimated laser beam propagating in a medium with a refractive index,  $n$ . In order to compensate for natural divergence of the beam, the medium should act as a distributed focusing lens. This means that the phase velocity of the beam,  $v_p = c/n$  shall be profiled by the medium according to the condition  $\partial v_p / \partial r > 0$ . The way to do this is to introduce a radial drop of the refractive index ( $\partial n / \partial r < 0$ ).

For application in particle accelerators, only a low density gaseous medium may be practical. However, because of the small gas refraction, a high increase of the gas density at the beam axis would be required to produce an appreciable lens effect. In a plasma, we have an opposite situation. Its refractive index is relatively strong and drops with the electron density,  $N_e$ , increase according to the equation

$$n = n_0 \sqrt{1 - \frac{e^2 \lambda^2 N_e}{\pi^2 m}} = n_0 \sqrt{1 - \frac{N_e}{N_{cr}}}, \quad (2)$$

where  $N_{cr} = \pi m c^2 / e^2 \lambda^2$  is the critical electron density. Hence, plasma appears to be a promising substance for optical channeling.

For  $N_e \ll N_{cr}$ , Eq.(2) takes the form

$$n = n_0 \left( 1 - \frac{e^2 \lambda^2 N_e}{2 \pi^2 m} \right). \quad (3)$$

It follows that the condition,  $\partial n / \partial r < 0$ , required for waveguiding may be satisfied in two ways: a) by profiling the electron density as  $\partial N_e / \partial r > 0$ , or b) using the relativistic growth of the electron mass,  $m$ , due to the ponderomotive electron motion induced by the laser field. Method (a) formulates the basics of laser guiding in plasma channels discussed in the present section. Effect (b) is responsible for relativistic self-focusing (RSF)<sup>22</sup>. Note that the relativistic increase of mass, when electrons oscillate in a strong electromagnetic field, goes along with a charge separation that may also bring to  $\partial N_e / \partial r > 0$ . It has been shown however, that, due to the inherent RSF instability, this process can not confine the laser beam over an appreciably long distance.<sup>23,24,25</sup> Then, preformed plasma channels become the most reliable choice for the extended confinement of the laser beam in plasma.

If the plasma density increases in a radial direction, refractive index drops according to the equation

$$\frac{\Delta n}{n_0} = -\frac{\Delta N_e}{2N_{cr}} \quad (4)$$

which follows from Eq.(2). When the refractive index drop satisfies conditions for total internal reflection, light will propagate like inside the fiber. For an electromagnetic wave incident onto the plasma layer at the angle  $\beta_0$  as shown in Fig.2, the condition for reflection is

$$n(r) \leq n_0 \sin \beta_0 \quad (5)$$

or for oblique incidence  $n(r) - n_0 \equiv \Delta n(r) \leq -n_0 \theta_0^2 / 2$  and

$$\Delta N_e \geq N_{cr} \theta_0^2. \quad (6)$$

If we consider a cylindrical plasma layer, for a focused Gaussian beam with a diffraction divergence

$$\theta_0 = \frac{\lambda}{\pi w_0}, \quad (7)$$

the condition for optical guiding is

$$\Delta N_e \geq \frac{mc^2}{\pi e^2 w_0^2} \equiv (\pi e^2 w_0^2)^{-1}. \quad (8)$$

Here,  $r_e = 2.82 \times 10^{-13}$  cm is the classic electron radius.

For example, a Gaussian laser beam focused into a spot with a radius of  $w_0 = 100$   $\mu$ m, will be trapped in a plasma waveguide with a "wall height" of  $N = 1.5 \times 10^{16}$  cm<sup>-3</sup>. Note that this condition does not depend upon the laser wavelength.

Two methods to produce plasma channels look feasible (see Fig.3). Both of them are based on using axicon focused laser beams. In the first method<sup>19</sup>, a linearly polarized beam focused by the axicon produces a circularly symmetric interference pattern along the axicon axis (see Fig.3a). The analytical solution for the radial component of the electric field  $E_L^r(r, z)$  is a Bessel function of the first kind of order 0:

$$E_L^r(r, z) = E_0(z) \times J_0(2\pi\theta_c r / \lambda) \quad (9)$$

with  $E_0(z) = 2\pi\theta_c \{2zI(z\theta_c) / \lambda\}^{1/2} \{\mu_0 / \epsilon_0\}^{1/4}$ ,

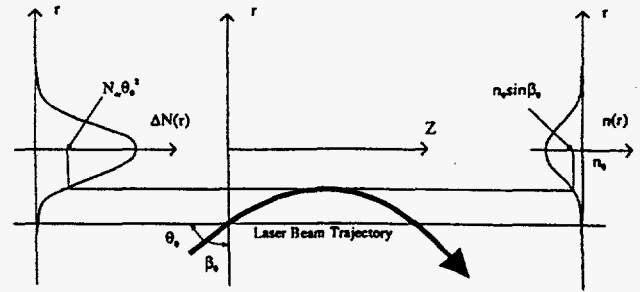


Fig.2 Reflection from plasma gradient at oblique incidence

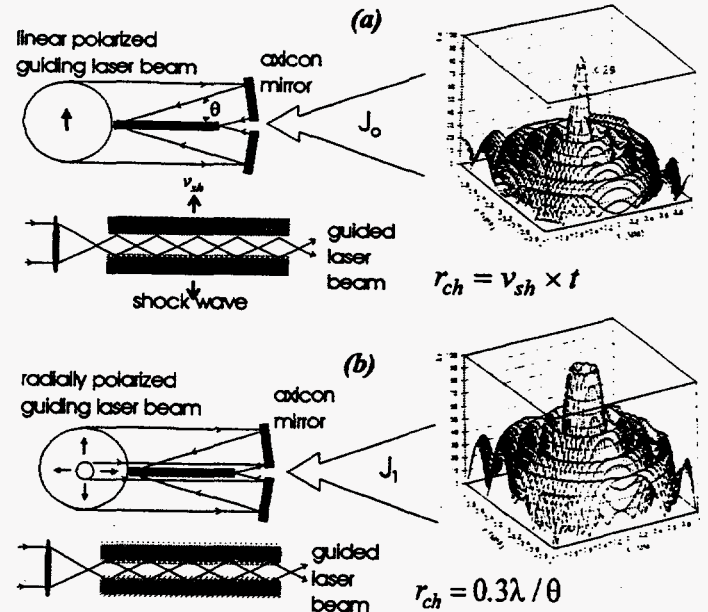


Fig.3 Channeling by axicon focused laser beams: a) expanding plasma channel by gas breakdown with linear polarized laser beam; b) stationary plasma channel produced by radially polarized laser beam.

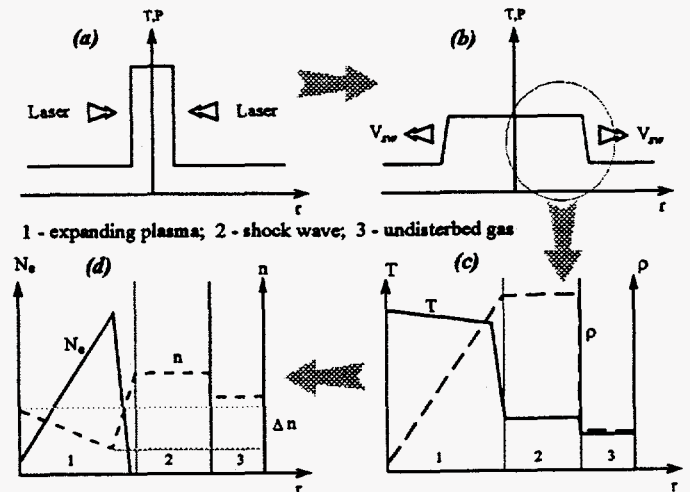


Fig.4 Plasma channel produced by cylindrical shock wave

where  $I(R)$  is the laser intensity distribution at the axicon,  $R$  is related to  $z$  by  $z=R/\theta_c$ ,  $\theta_c$  is the double apex angle of the axicon.<sup>4</sup> The radial position of the first minimum in the distribution Eq.(9) is at

$$r_{min}=0.38\lambda/\theta_c. \quad (10)$$

We see that the laser field is not profiled to produce the  $\partial N_e/\partial r > 0$  distribution immediately via direct ionization.

To understand the processes leading to the plasma channel formation using  $J_0$ -shaped intensity distribution, let us address the diagram presented in Fig.4.

At the first stage of the process, plasma is produced along the  $z$ -axis by tunneling and avalanche ionization. When the inverse bremsstrahlung absorption coefficient of the plasma,

$$\mu_\omega \approx 0.1 N_e v_{eff}/\omega^2, \quad (11)$$

where  $v_{eff}$  is the effective electron-atom collision efficiency, reaches the inverse distance of optical ray propagation across the focal region, that is  $\mu_\omega \approx \theta_c/2r_{min}$ , the input laser radiation is absorbed within the first Bessel maximum.

Intense plasma heating within the narrow region near the axis results in a local temperature increase to  $\sim 50,000$  °K and the proportional adiabatic pressure jump that generates a cylindrical detonation wave expanding with a supersonic velocity outwards. Behavior of such a wave is similar to the propagation of high-current discharges or explosive combustion waves and has been extensively studied previously.<sup>26</sup> A shock wave, pushing the gas as a supersonic piston, produces a discontinuity of much higher amplitude than the ambient gas density and leaves a rarefied channel behind. Typical distributions of the gas density and temperature in a shock wave are sketched in Fig.4c. The superposition of  $\rho$  and  $T$  distributions explains a characteristic electron density distribution shown in Fig.4d that features a positive gradient  $\partial N_e/\partial r > 0$  desired for waveguiding. Optical waveguiding under these conditions has been already demonstrated.<sup>19</sup>

Another similar method uses radial polarized laser beam to form a  $J_1$  Bessel distribution<sup>20</sup> (see Fig.3b). This provides a field naturally shaped with interferometric precision to produce gas ionization appropriate for waveguiding. The radial position of the first maximum occurs at

$$r_{max}=0.29\lambda/\theta_c \quad (12)$$

and is equal to  $170 \mu\text{m}$  for a representative case of  $\lambda=10.6 \mu\text{m}$  and  $\theta_c=20$  mrad.

The next step is to convert this favorably shaped electric field into the corresponding cylindrical plasma density distribution by means of gas ionization. We consider a cascade ionization mechanism that requires relatively low level of laser irradiation. The characteristic rate of plasma formation has a quadratic dependence upon  $\omega$ . This means that using a  $\text{CO}_2$  laser, 100 times less intensity is required to produce the same avalanche ionization effect as compared with a Nd laser.

A method for generating a radially polarized  $\text{CO}_2$  laser beam and its focusing by an axicon mirror has been demonstrated during the course of the ICA experiments.<sup>6</sup> According to this method, a linearly polarized laser beam is converted into one with radial polarization by using a double interferometer.<sup>27</sup> Actually, gas breakdowns of submillimeter diameter and  $\sim 10$  cm length have been produced already as a side effect of the ICA experiment. We just need to test how well laser radiation will be guided along such a channel. Still another relatively simple way of producing high-power picosecond laser pulse channeling inside a dielectric capillary should not be ruled out.

#### IV. $\text{CO}_2$ Laser Driver for a Laser Wakefield Accelerator

It looks logical to use a high-power  $\text{CO}_2$  laser, which is a strong ionizer, in the schemes where such ionization and related effects are not problems but are desirable, as it happens in plasma accelerators. Here, we review principles of laser wakefield acceleration in order to introduce basic equations that will be used in analysis.

Wave packet on Fig.5 ponderomotively separates charges initiating their oscillation at the plasma eigenfrequency,  $\omega_p$ , that depends upon the electron density,  $N_e$ , by

$$\omega_p = 2e \left( \frac{\pi N_e}{m} \right)^{1/2}. \quad (13)$$

Maximum of the periodical accelerating field due to the longitudinal charge separation is defined by wave breaking limit,

$$E_a^{\max} \approx mc\omega/e. \quad (14)$$

Plasma wave follows the laser pulse with a phase velocity equal to the group velocity of the laser pulse,  $v_{ph} = cn$ , where

$n = (1 - \omega_p^2/\omega^2)^{1/2}$  is a plasma refractive index.

Relativistic particle propagating together with plasma wave will slip out of synchronism at the distance

$$l_a \approx \lambda_p \left( \omega/\omega_p \right)^2. \quad (15)$$

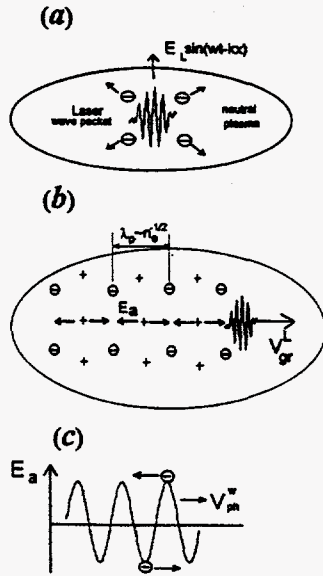


Fig.5 Laser excited plasma wake:

- a) wave packet ponderomotively separates charges; b) charges are regularly grouped behind the traveling laser pulse;
- c) plasma wave follows the laser pulse, accelerating trapped electrons.

Multiplying maximum acceleration gradient by maximum dephasing distance, we obtain maximum net acceleration  $\gamma_{\max} \propto (\omega/\omega_p)^3$ .

Next question is how to approach this theoretical maximum of acceleration. What is the most efficient way to excite strong and regular plasma wave? In LBWA scheme (see Fig.6a) we choose periodical force that matches the plasma frequency and resonantly enhances the plasma oscillations.

In LWFA scheme (Fig.6b), you give the plasma a strong shock that is not as much efficient for wave excitation as a resonance force. However, it is the simplest scheme. Note, that after developing a short-pulse CO<sub>2</sub> laser, there will be the first-time opportunity to use CO<sub>2</sub> laser in this scheme.

The third, SMLWFA scheme (Fig.6c), looks the most promising. It comes to the scene when the laser pulse is relativistically strong. Relativistically strong means that laser power,  $P$ , satisfies the condition of relativistic self-focusing

$$P \geq 17(\omega/\omega_p)^2 [GW]. \quad (16)$$

In this case, initially small plasma density oscillations cause modulation at the plasma frequency of the laser beam envelope and its intensity. Then, the pulse resonantly enhances the plasma oscillation similar to a beat wave scheme matched automatically to a local plasma density. It is understood that the laser pulse length shall extend over several plasma periods.

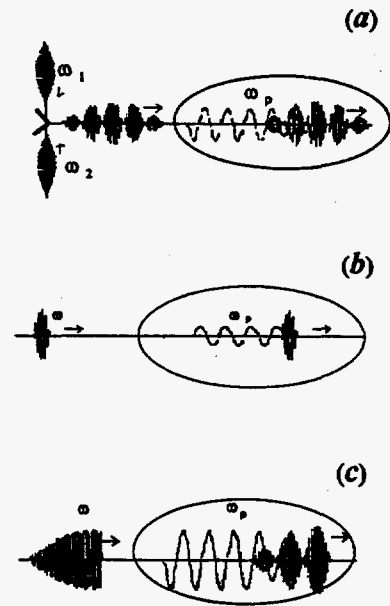


Fig.6 Laser-driven plasma accelerators:

- a) laser beat wave accelerator (LBWA), requires two laser beams with  $\omega_1 - \omega_2 = \omega_p$ ; b) laser wakefield accelerator (LWFA), requires short laser pulse  $\tau_L \approx \lambda_p/2c$ ; c) self-modulated LWFA, requires relativistically strong laser pulse.

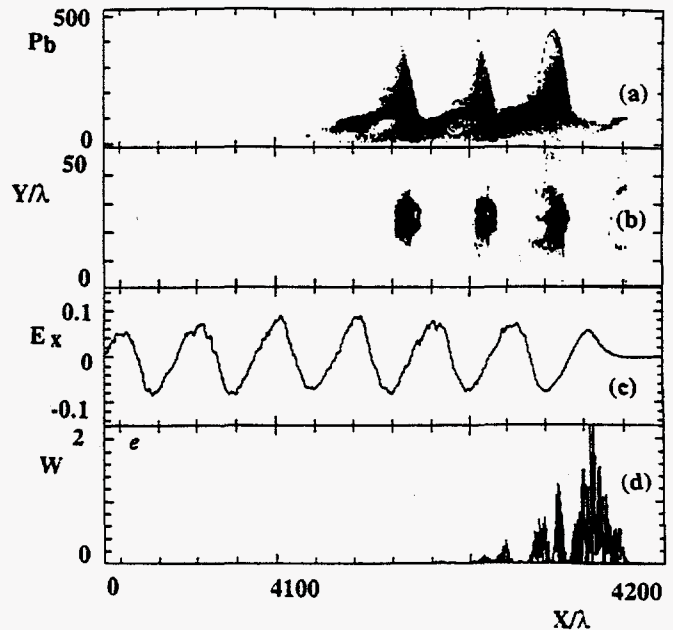


Fig.7 Electron acceleration in prefilled plasma channel with an s-polarized laser pulse at  $a=1$ ,  $\omega_p^{ch}/\omega = 0.065$ ,  $\omega t/2\pi = 4000$ ,  $E_e^0 = 50$  MeV.<sup>21</sup> a) longitudinal phase space of the beam electrons; b) x-y distribution of the beam electrons; c) longitudinal wake electric field; d) profile of the pulse electromagnetic energy.

It has been shown by simulations that, if the laser pulse is just strong and long, it is not enough to produce a strong and regular wake.<sup>21</sup> The wake needs an efficient initiation. Fig.6c illustrates one of the possibilities where a steep leading front, with  $\tau_{fr} < \lambda_p / c$ , serves as a good initiator for a plasma wave. How will the CO<sub>2</sub> laser work in this scheme? Simulations have been done for a 4-TW, few picosecond, properly shaped CO<sub>2</sub> laser pulse propagating in a plasma channel.<sup>21</sup> The predicted maximum electron energy is 500 MeV (see Fig.7).

Finally, let us address the question of how to compare potential performance of 10- $\mu$ m and 1- $\mu$ m lasers in this promising configuration. We rewrite here relevant formulas. Realistically attainable for this configuration, the accelerating field depends upon the normalized laser field strength  $a$ :

$$E_a \propto \omega a^2 / \sqrt{1+a^2} / 2, \quad (17)$$

where  $a \equiv eE_L / m\omega c$  and  $E_L$  is the laser field amplitude. For fixed laser field,  $a$  is proportional to wavelength. This is actually the consequence of stronger ponderomotive potential at higher  $\lambda$ . In spite of this fact, the expression for the net acceleration

$$\gamma_{\max} \approx a(\omega/\omega_p)^3 \quad (18)$$

still looks very discouraging for CO<sub>2</sub> lasers and beneficial for shorter wavelength lasers. However this first impression is misleading. The thing is that we are not free in making the choice for parameters entering Eq.(18). The values of  $\omega$  and  $\omega_p$  are interrelated through the self-focusing condition, Eq.(16).

Assume for our wavelength comparison laser beams of equal power close to the critical self-focusing condition. Then we come to the conclusion that the ratio  $\omega/\omega_p$  shall be chosen equal for any laser wavelength. The result is that the maximum acceleration is proportional to  $\lambda$ :  $\gamma_{\max} \propto P^2 / \omega$ . Remember, that we arrive to this conclusion assuming the laser fields of equal amplitude and, hence, laser beams focusing to the equal spot size. For instance, it is the case when we consider acceleration inside a waveguide of a particular diameter. When  $\lambda=1 \mu\text{m}$ , we need to channel the laser beam and, hence, e-beam in a 10  $\mu\text{m}$  waveguide in order to obtain similar acceleration as with a CO<sub>2</sub> laser beam in a 100  $\mu\text{m}$  waveguide. Doing it, we may encounter severe problems with the electron beam scattering. When we increase  $\omega$  and  $\omega_p$  10 times, we increase plasma density 100 times, according to Eq.(13), with the proportional increase of the multiple scattering in the gas described by formula<sup>28</sup>

$$\Delta\theta_{1/e} = \left( \frac{W_s}{W} \right) \left( \frac{z}{L_R} \right)^{1/2} \left[ 1 + 0.1 \log_{10} \left( \frac{z}{L_R} \right) \right], \quad (19)$$

where  $\Delta\theta_{1/e}$  is the angular spread of the e-beam,  $W$ [MeV] is the mean electron energy,  $W_s=19.7$  MeV is a multiple scattering constant,  $z$  is the path length through the gas traversed by the electron, and  $L_R$  is the radiation length of the medium, which for hydrogen gas is  $L_R=7 \times 10^5$  [cm]/p[atm]. The result of gas scattering is the e-beam emittance growth and reduced acceleration efficiency due to a poor overlap of the expanded e-beam with the narrow channeled laser beam. A simplified formula for the e-beam expansion due to the multiple scattering

$$\Delta r(z) = \frac{2}{3} \frac{W_s}{W \sqrt{L_R}} z^{3/2} \quad (20)$$

indicates that the e-beam expands 10  $\mu\text{m}$  in radius after passing 2 cm distance in a 1/4 atm of H<sub>2</sub>.

It follows that the CO<sub>2</sub> laser, which permits 10 times bigger waveguide and e-beam diameters and a 100 times lower pressure, looks more attractive for prospective high-energy plasma accelerators.

Considering the feasibility of conducting a sub-GeV plasma acceleration experiment at the ATF, we should remember that not just a terawatt CO<sub>2</sub> laser will be available for this purpose, but also one of the world's brightest e-beams that may be fitted inside a 100- $\mu\text{m}$  wide channel.

## V. Conclusion

CO<sub>2</sub> lasers are potentially attractive as plasma accelerator drivers because of the 100 times stronger ponderomotive action of its radiation compared with more extensively used 1- $\mu\text{m}$  lasers. Note that the ponderomotive action is the foundation of such key processes in plasma-based accelerators as avalanche and tunnel ionization, relativistic self-focusing, and plasma wake excitation. Being scalable to high energies and high repetition rates, CO<sub>2</sub> lasers may be considered among the next-generation particle accelerator drivers.

Despite this advantage, CO<sub>2</sub> lasers were not specified so far for LWFA experiments for two reasons: relatively long pulse duration, and a  $\lambda$ -proportional diffraction divergence that sets a short Rayleigh interaction range.

The terawatt-class picosecond CO<sub>2</sub> laser which is presently under development at the ATF, with its short pulse duration down to 3 ps, solves the first issue. Due to its unique set of parameters, the ATF laser presents new opportunities in laser

acceleration study. For instance, because of the short pulse duration the ATF CO<sub>2</sub> laser may be used to study a LWFA scheme in a long-wavelength spectral region.

The diffraction problem will be relieved by plasma waveguiding. Actually, this problem is common for any laser-driven plasma accelerator scheme. Waveguiding in a plasma channel is insensitive to the laser wavelength and should work for a CO<sub>2</sub> laser as well as for Nd:YAG lasers. In addition to it, a CO<sub>2</sub> laser is a good choice to produce a plasma channel.

The proposed study of laser wakefield acceleration in a plasma channel may be a good addition to the ATF experimental program that already includes two far-field accelerator schemes, ICA and IFEL, and one near-field scheme, Laser Linac. A plasma accelerator experiment will utilize in the most efficient manner the low-emittance 70-MeV e-beam, already available at the ATF, and a terawatt CO<sub>2</sub> laser which is under development. Simulation shows that this combination may lead to a 500 MeV acceleration demonstration in a single 4 cm long acceleration stage.

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