**ELECTRON ACCELERATION
IN PREFORMED PLASMA CHANNELS
WITH TERAWATT CO₂ LASER**

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Abstract

Extended cylindrical plasma channels produced under gas breakdown by axicon-focused laser beams may be used as optical waveguides in laser-driven electron accelerators. Plasma channeling of the laser beams will help to maintain a high acceleration gradient over many Rayleigh lengths. In addition, the rarefied gas density channel produced after the optical gas breakdown, and followed by a plasma column expansion, reduces multiple scattering of the electron beam. A high-power picosecond CO₂ laser operational at the ATF and being further upgraded to the 1 TW level is considered as the source for a plasma channel formation and as the laser accelerator driver. We show how various laser accelerator schemes including beat wave, wake field, and Inverse Cherenkov accelerator benefit from using a channeled short-pulse CO₂ laser as a driver.

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Symbols

A	tunneling ionization rate
A_0	amplitude of laser vector potential
a_L	unitless laser strength parameter (normalized vector potential)
B	tunneling ionization probability
c	speed of light in vacuum
E_a	accelerating longitudinal electric field
E_{DC}	DC electric field
E_L	transverse laser electric field
E_L^r	radial projection of E_L
E	laser fluence (J/cm^2)
E_s	saturation fluence
$\mathcal{E}$	laser energy
$\mathcal{E}$	thermodynamic energy
g_0	small signal gain
h	Planck constant
I	laser intensity
I_{th}	breakdown threshold intensity
L_d	laser pulse depletion length
L_{int}	diffraction limited interaction region
L_{ph}	phase detuning length
L_R	radiation length
l	amplifier length
m	electron mass
N^*	population of upper laser level
N_{cr}	critical electron density
N_e	electron plasma density
N_m	gas density
n	refractive index
P_{cr}	critical laser power, relativistic self-focusing threshold
P_L	laser power
p	gas pressure
R	radial coordinate at reflector
r	coordinate perpendicular to e-beam

r_e	electron radius
r_{ch}	radius of hollow channel
r_{max}	position of first maximum in J_1 Bessel distribution
r_{min}	position of first minimum in J_0 Bessel distribution
S	amplifier aperture
$S(\nu)$	power spectral density
T	temperature
t	time
V	volume
v	electron speed
v_g	group velocity
v_{ph}	phase velocity
v_{sw}	shock wave velocity
U_i	ionization potential
W_{ocs}	electron pondermotive potential
W_s	multiple scattering constant
ΔW	energy gain
w_0	laser waist radius
z	coordinate along e-beam
z_0	Rayleigh distance
β	normalized speed of electron
β_0	angle of incidence
γ	Lorentz factor for longitudinal motion
γ_1	Lorentz factor for transverse motion
γ_0	adiabatic constant
δ	electron plasma density modulation in plasma wave ($=\Delta N_e/N_e$)
δ_s	saturated δ
ϵ_0	electric permittivity in vacuum
η	efficiency ($=E_d/E_L$)
η_s	saturated efficiency
θ_0	diffraction divergence, also $90^\circ - \beta_0$
θ_c	double apex angle of axicon (Cherenkov angle)
$\Delta\theta_{1/e}$	angular spread of electron beam
λ	laser wavelength

λ_p	plasma wavelength
μ	electron mobility
μ_0	magnetic permeability in vacuum
μ_ω	absorption coefficient
ν	frequency
ν_{eff}	effective electron-atom momentum transfer collision frequency
ρ_0	gas density
σ	elastic scattering cross-section
σ_g	gain cross-section
τ_L	laser pulse duration
χ	specific heat
ω	angular laser frequency
ω_p	angular plasma frequency

Section 1

Introduction

With contemporary terawatt picosecond lasers, extremely high intensity levels, $I=10^{16}$ - 10^{18} W/cm², are attainable upon the tight focusing of laser beams. By the fundamental equation $I=(1/2)\epsilon_0 c E_L^2$, the transverse electric field corresponding to such intensities is $E_L=3$ - 30 GV/cm. Several schemes based on the interaction of electron beams directly with laser radiation, as in the Inverse Cherenkov Accelerator (ICA)[1,2] and Inverse Free Electron Laser (IFEL) Accelerator[3,4], or with laser-produced wake fields, such as Grating Linac[5,6], Laser Wake Field Accelerator (LWFA)[7,8], and Laser Beat Wave Accelerator (LBWA)[7,9], are under development to convert a portion of this enormous field into a longitudinal accelerating field. Recently demonstrated high-gradient electron acceleration using LBWA[10,11], LWFA[12,13], and ICA[14] schemes gives promise for further advancement of laser accelerator concepts towards practical devices.

LBWA and LWFA schemes are based on trapping and acceleration of electron bunches by the electrostatic potential developed due to a periodic electron-ion space charge modulation within a laser-generated plasma wave. The longitudinal electric field associated with such a wave is $E_a=\delta N_e^{1/2}$ [V/cm], where N_e is an average plasma density in cm⁻³ and $\delta=\Delta N_e/N_e$ is the electron density modulation in a plasma wave. For example, for $N_e=10^{17}$ cm⁻³ and $\delta=10\%$, $E_a=3$ GeV/m. However, the intrinsic limitation for these schemes is a short diffraction limited interaction region, L_{int} , in which the required high laser intensity may be maintained. The length of this region is related to the Rayleigh distance, z_0 , measured from the focal point to the point where the laser beam expands two times in a cross-sectional area, by the ratio $L_{int}\approx\pi z_0$. For Gaussian beams, z_0 is related to the waist radius, w_0 , and laser wavelength, λ , by the ratio $z_0=\pi w_0^2/\lambda$.

For typical conditions of plasma acceleration experiments $\lambda=1.06$ μ m and $w_0=50$ μ m,[12] or $\lambda=10.6$ μ m and $w_0=150$ μ m,[10] therefore $z_0=6$ - 8 mm. This restricts the energy gain, ΔW , attainable in a single-stage LBWA and LWFA, driven by a terawatt-class laser, to $\Delta W=E_{acc}L_{int}\approx 100$ MeV level that is not attained yet.

To reach the next milestone of $\Delta W=1$ GeV, more powerful lasers and/or longer interaction regions would be needed. However, extremely high laser power (e.g., petawatt) with corresponding 1 TV/cm electric fields may be more destructive than productive for plasma-based accelerators due to pondermotive blow out of the ion plasma from the Rayleigh region.[15]

Another possible way to increase the net acceleration without scaling up the laser driver power is optical guiding. Optical guiding options, applicable to plasma-based accelerators considered in the literature include relativistic self-

focusing and preformed plasma density channels.[16,17] Relativistic self-focusing is due to relativistic oscillations of plasma electrons in the laser field. It may be observed with relativistically strong laser radiation that satisfies the power requirement $P_L > P_{cr} = 17(\lambda_p/\lambda)[\text{GW}]$, where λ_p is the plasma wavelength that depends upon N_e . [18] For typical values of $\lambda = 1 \mu\text{m}$ and $N_e = 10^{17} \text{ cm}^{-3}$, $P_{cr} = 2 \text{ TW}$. However, it has been shown by simulations[19] that relativistic self-focusing does not prevent the leading portion of a laser pulse from diffraction and does not work for short laser pulses with a duration $\tau_L \leq \lambda_p/c$. The efficiency of relativistic self-focusing for longer pulses is presently under study.[20,21]

The preformed plasma density channel concept itself or in combination with relativistic self-focusing looks the most promising for producing stable waveguiding conditions. Optical waveguiding over $\sim 20z_0$ was already experimentally demonstrated in a gas breakdown channel produced by an axicon focused linearly polarized laser beam.[22] In Section 2, we consider this method and a closely related plasma waveguide formation by a radially polarized laser beam[23] for demonstration of optical channeling in the range of the experimental conditions typical for laser acceleration schemes. The referred experiment and simulations on radiation channeling in plasma prove the viability of the discussed methods for laser accelerators.

We would not rule out also the potential of more conventional hollow waveguides for channeling of ultra-intense laser beams. A laser beam with intensity at the level of 10^{16} W/cm^2 injected inside a capillary tube will produce wall ablation. However, there is a possibility that the plasma layer developed by a picosecond pulse, being just a portion of the laser wavelength thick, will not attenuate the laser beam significantly. Also, after plasma expansion inside the hollow channel, waveguiding of the second delayed laser pulse in the narrow underdense plasma channel may be obtained. There are suggestions to use such an approach in x-ray laser study [24]. However this method was not explored so far experimentally.

To a great extent the present study is stimulated by the ongoing development at the ATF of a new high-power laser source, a 10-ps (with the possibility of upgrading to 3 ps) 1-TW CO_2 laser [25] that is expected to be operational in 1996. This device presents new opportunities as a laser accelerator driver due to its long wavelength, $\lambda \approx 10 \mu\text{m}$, few picosecond pulse duration, and terawatt peak power. So far, terawatt picosecond pulses were produced only with solid state and excimer lasers operating in UV to near IR spectral regions ($0.25\text{--}1 \mu\text{m}$). (Previously known high peak-power CO_2 lasers demonstrated up to several terawatt power in a longer pulse, such as a 30-TW $\sim 1\text{-ns}$ Antares [26], or 2-ps pulses at $\sim 1\text{-GW}$ power [27].) Such a combination of laser parameters was not explored so far and looks promising for a number of applications. For instance, one order of magnitude increase in wavelength results in two orders of magnitude higher the pondermotive potential, $W_{osc} = e^2 E_L^2 / 2m\omega^2$, of the electron oscillating in the electric field of the laser beam. The result of this is the proportional scaling of such pondermotively driven plasma processes as an avalanche electron multiplication, plasma wave generation, relativistic self-focusing, etc. Such mechanisms play a key role in plasma accelerators and plasma waveguide development. In Section 3, we discuss possible applications of a picosecond CO_2

laser driver and plasma waveguiding concepts in plasma wave and ICA electron accelerators. We consider the feasibility of conducting such experiments at the ATF that would explore new opportunities provided by the terawatt picosecond ATF CO₂ laser.

In the Conclusion we summarize advantages of high-power picosecond CO₂ laser for waveguiding and plasma acceleration.

In Appendix A, we give brief theory and calculations for a plasma development in a gas under a CO₂ laser irradiation.

Appendix B gives an insight into the operational status of the ATF, its active laser acceleration research program and upgrade prospects.

Section 2

Plasma Waveguide

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 it drops with the density increase. This is why a plasma looks like the most promising substance for optical channels with a low electron scattering.

In a plasma, the refractive index depends upon the electron density N_e and laser wavelength λ according to the equation

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

where $N_{cr} = mc^2 \pi / e^2 \lambda^2$, known as the critical electron density. For $N_e \ll N_{cr}$, Eq.(1) takes the form

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

It follows, that the waveguiding condition $\partial n / \partial r < 0$ 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 pondermotive 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)[18] that may be observed under the experimental conditions also discussed below. Note that the relativistic increase of m , when electrons oscillate in a strong electromagnetic field, goes along with a charge separation that may also bring $\partial N_e / \partial r > 0$.

Basic mechanisms of plasma development in gases under the intense CO_2 laser irradiation, avalanche and tunneling ionization, are described in Appendix A. In the present section we describe methods for generating preformed plasma channels and present compiled simulation results on the intense laser pulse propagation in plasma channels.

2.1 OPTICAL REFLECTION ON PLASMA GRADIENTS

The idea of a preformed plasma waveguide is based on changing the refractive index in a medium due to a developed plasma density gradient according to the equation

$$\frac{\Delta n}{n_0} = -\frac{\Delta N_e}{2N_{cr}} \quad (3)$$

This follows from Eq.(1) under the approximation of $N_e \ll N_{cr}$. For an electromagnetic wave incident onto the plasma layer at the angle β_0 as shown in Fig. 1, the condition for reflection is according to Snell's law

$$n(r) \leq n_0 \sin \beta_0, \quad (4)$$

or for oblique incidence

$$n(r) - n_0 \equiv \Delta n(r) \leq -n_0 \theta_0^2 / 2,$$

and by Eq.(3)

$$\Delta N_e \geq N_{cr} \theta_0^2. \quad (5)$$

Fig. 1

Optical ray trajectory in a plasma layer with a radial density distribution $N_e(r)$ and corresponding index profile $n(r)$

If we consider a cylindrical plasma layer with the "wall height" satisfying Eq.(5), then for a focused Gaussian beam having a diffraction divergence

$$\theta_0 = \frac{\lambda_L}{w_0 \pi} \quad (6)$$

the condition of optical guiding inside a plasma cylinder is

$$\Delta N_e \geq \frac{mc^2}{e^2 w_0 \pi} \equiv (r_e w_0^2 \pi)^{-1}, \quad (7)$$

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

For example, a Gaussian laser beam focused into a spot with a radius of $w_0 = 100$ μm will be trapped in a plasma waveguide with $\Delta N_e = 1.5 \times 10^{16} \text{ cm}^{-3}$ at the "wall". Note that the criteria of waveguiding, Eq.(7), does not depend upon the laser wavelength.

The estimated reflection conditions are applied to the following waveguiding methods that may be used to extend the interaction length in plasma accelerators. They are also referred to when estimating the limits of the ICA scheme due to gas breakdown as well as for the axicon focused laser beam recycling.

2.2 METHODS OF PLASMA CHANNEL FORMATION

We describe in this section three methods to produce the extended axial plasma density distributions with a positive gradient $\partial N_e / \partial r > 0$, desired for waveguiding. The first two methods utilize an axicon (conical analog for a positive lens or mirror) to converge collimated incident beams along the optical axis.

The first method, described in paragraph 2.2.1.1, is based on using axicon-focused *radially* polarized laser beams. A negative gradient $\partial N_e / \partial r < 0$ is developed near the axis upon axicon focusing a J_1 Bessel type intensity distribution. We just let this favorably shaped field produce a similarly shaped plasma via gas ionization. This process does not include the ion motion and may be easily understood analytically. The proposed method provides good control of the waveguide parameters and requires relatively low laser drive power. However, its realization requires, in addition to a laser, the application of a fast electric discharge. Taking into the account the constant radius of the waveguide produced by this method, we refer to it as a "stationary" waveguide.

The second "dynamic" waveguide method, where the plasma channel is expanding with a supersonic speed, is described in paragraph 2.2.1.2. This method does not require an additional discharge or a complex radial polarization converter. It is based on using a *linearly* polarized beam in the same axicon focusing geometry. A waveguiding plasma density channel will be produced inside the expanding cylindrical shock wave after laser-initiated gas breakdown along the axicon axis. Because of complicated gas dynamics, this effect is not readily predictable without rigorous computer simulations. A good thing is that this method really works, as has been experimentally demonstrated.[22]

The third method is based on using a regular waveguiding capillary tube. A possibility of using this method is considered in paragraph 2.2.3

2.2.1 Axicon Focused Laser Beams

2.2.1.1 Stationary Plasma Channel

The recently proposed method of long plasma waveguide formation is based on axicon focusing of a short, radially polarized CO_2 laser pulse into a

uniform, low density discharge plasma.[23] This method utilizes the axicon property to produce a J_1 axisymmetric Bessel distribution of the electric field extended along the optical axis of the axicon by focusing a radially polarized laser beam in a configuration sketched in Fig.2.[1] This provides a field naturally shaped with interferometric precision to produce a cylindrical plasma density distribution appropriate for waveguiding.

Fig.2
Axicon focusing geometry.

A method for generating a radially polarized CO_2 laser beam[28] and its focusing by an axicon mirror has been demonstrated during the course of the ICA experiments.[14] According to this method, a linearly polarized laser beam is converted into one with radial polarization by using a double interferometer.[28]

When a radially polarized beam is focused by the axicon a circularly symmetric interference pattern is developed along the focal region of the axicon. 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 1:

$$E_L^r(r, z) = E_0(z) \times J_1(2\pi\theta_c r/\lambda) \quad (8)$$

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

where $I(R)$ is the laser intensity distribution at the axicon, R is related to z by $z = R/\theta_c$, θ_c is the double apex angle of the axicon.[1] The radial position of the first maximum in the distribution Eq.(8) occurs at

$$r_{\max} = 0.29\lambda/\theta_c, \quad (9)$$

and is equal to $170 \mu\text{m}$ for a representative case of $\lambda = 10.6 \mu\text{m}$ and $\theta_c = 20 \text{ mrad}$. The electric field profile described by Eq.(8) is plotted in Fig.3. The engineering formula corresponding to Eq.(8) is

$$E_L^r(r_{\max}, z) [\text{TV/m}] = 5.8 \times 10^{-9} (I(R) [\text{W/cm}^2] z [\text{cm}])^{1/2}. \quad (10)$$

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 levels of laser irradiation. From Eq.(A6), the characteristic rate of plasma formation has a quadratic dependence upon ω . This means that using a CO₂ laser, 100 times less intensity is required to produce the same avalanche ionization effect as compared with a Nd laser.

Fig.3

Spatial distribution of a radial polarized laser beam after axicon focusing.

As was mentioned above, the principal advantage of using an axicon focusing element, in addition to getting a J_1 Bessel distribution, is an extending of the region of a tight laser energy concentration over many Rayleigh lengths. The length of this region is actually limited by the initial laser beam diameter and the axicon apex angle as is illustrated by Fig.2. Neglecting diffraction, the distribution $E_\theta(z)$ for a Gaussian input beam profile described by $I(R)=I_0 \exp(-2R/\Delta)^2$ with $\Delta=5$ mm (see Fig.4a) is shown in Fig.4d. In practice, the axicon may have a hole in the middle to introduce the guided laser beam and/or electron beam for laser acceleration. In order to avoid losses in the center of the axicon-focused beam, the beam can be made annular in shape by using an additional axicon telescope. The radial distribution obtained after axicon telescoping of a Gaussian beam is presented in Fig.4b. Although it looks quite different from the original distribution presented in Fig.4a, axicon focusing of distribution (4b) results in an axial distribution similar to (4d) but shifted along z -axis by a distance equal to the divided by θ_c radial expansion of the axicon telescope (do not confuse with the final focusing axicon lens or mirror). Note, that in order to obtain a constant field amplitude along the z -axis, which is desirable for a more uniform plasma waveguide development along the z -axis, it would be necessary to tailor the radial field distribution close to the way shown in Fig.4c.

It is easy to see that creating a plasma waveguide requires more than just the presence of the laser beam. By comparing Eqs.(6) and (9), we see that the conditions are identical for reflection of a Gaussian beam with a waist w_0 and for an axicon-focused beam used to generate a J_1 plasma profile with $r_{max}=w_0$. This means that the J_1 distribution will be distorted, due to the axicon-focused beam refraction on the laser-produced plasma, before waveguide conditions are reached. A possible solution to this problem is to use an additional external electric field. Note that according to the similarity principle, avalanche breakdown theory is also applicable to DC fields after replacing ω by ν_{eff} and E_L by E_{DC} in Eq.(A6) and later. Such a short rise time, above-breakdown, DC electric field started prior to the laser pulse will produce a uniform plasma. Then, the laser pulse applied on top of the DC field, by enhancing the ionization in a maximum of the laser field, produces a J_1 -type spatial modulation of the electron density. The absolute amplitude of the plasma density modulation, ΔN_e , at the moment of the laser pulse termination is chosen to be well below the magnitude required for waveguiding or reflection of the axicon-focused beam. After the laser pulse termination, the continuing exponential growth of the plasma density under the DC field ultimately brings ΔN_e to the value required for waveguiding. The laser beam to be guided will be injected inside the plasma channel before the total breakdown of the gas occurs.

Fig.4

Distributions of laser intensity along the axicon axis $I(z)=z\theta_c P(z\theta_c)$ for $\theta_c=20$ mrad against initial laser beam profiles $P(R)$: a) Gaussian beam, b) axicon telescoped Gaussian beam, c) hyperbolic beam ($P(R)\sim 1/R$).

Care should be taken that the spatial modulation of the plasma density produced by the J_1 -profiled laser beam and enhanced by the DC field should not be washed out by diffusion before the guided beam is injected into the waveguide.

Under the DC electric field with the above-breakdown amplitude, the major process of the plasma channel distortion is electron drift with a velocity of

$$V = \mu E_{DC} \quad (11)$$

where μ is the electron mobility, which is inversely proportional to the gas pressure and is equal to $\mu \approx 1000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \text{ atm}$ for H_2 . [29] Comparing Eqs. (A6) and (11), we see that plasma density growth depends upon the field amplitude much more than the electron drift. This means there should always be a high enough field to produce a waveguide plasma profile faster than it is distorted by electron drift. The impact of the electron drift may be further reduced if the electric field is directed along the axicon axis. An example of such a situation is an accelerating microwave field in a linac cavity. We assume therefore, that the distortion of the plasma channel due to electron drift or thermal diffusion has a characteristic time longer than the time interval for the waveguide development measured from the beginning of the laser pulse.

The simulations for plasma waveguide development in hydrogen gas are illustrated in Fig. 5. The DC or microwave electric field of 8.2 kV/cm is chosen to produce a 10-times electron multiplication in a 1-ns time interval. The axicon-focused CO_2 laser beam with a Gaussian temporal pulse shape of 100-ps duration produces a 2-times electron multiplication in the first maximum of its J_1 radial Bessel distribution, where the peak intensity is equal to 3.5 GW/cm^2 . Under these conditions, we get $\Delta N_e = 10^{15} \text{ cm}^{-3}$ 1 ns after the laser pulse maximum. 1 ns later, due to the continuing 10 times electron density multiplication under the electric field, we expect $\Delta N_e = N_e(0) = 10^{16} \text{ cm}^{-3}$, conditions adequate for guiding a Gaussian pulse focused into a spot with $w_0 = 120 \text{ }\mu\text{m}$.

Fig. 5

Plasma density profile produced by stationary method at H_2 pressure 0.17 atm, DC(RF) field 8.2 kV/cm, $N_e(0) = 10^9 \text{ cm}^{-3}$, CO_2 laser peak intensity 1 GW/cm^2 ; Gaussian pulse $I(t) = I(0) \exp\{-(2t/\tau)^2\}$ with $\tau = 350 \text{ ps}$ reaches maximum at $t = 5 \text{ ns}$: a) dynamics of plasma density profile, b) radial plasma density distribution at $t = 6 \text{ ns}$.

It should be understood, that the preceding parameters were chosen as a way of illustration and may be varied depending upon the particular application requirements and other practical considerations. For instance, the electric field increase from 8 kV/cm to 40 kV/cm speeds up the electron multiplication 25 times. Other operational parameters also may be varied.

If to increase the hydrogen pressure to 1.7-2 atm, the example illustrated in Fig.5 is of practical interest for the ICA experiment. At lower gas pressure, the transverse electron drift according to Eq.(11) tends to distort the plasma channel. To make the required electron multiplication in the transverse electric field faster than the plasma channel distortion, the electric field should be increased proportionally to $1/p^2$. E.g., with a 50 kV/cm transverse electric field, a stationary method should work well at the gas density $N_m \approx 10^{19} \text{ cm}^{-3}$, that is applicable to the conditions of the NRL self-modulated Laser Wake Field Accelerator (LWFA) experiment (see Section 3).

2.2.1.1 Dynamic Plasma Channel

A technically similar but physically different method of the optical guiding in the preformed plasma channel has been demonstrated recently.[22] This method also explores the axicon property to concentrate the incoming laser beam in a narrow cylindrical volume extended along the axicon axis but uses the more traditional linearly polarized input beam. In this case, the radial field distribution in the axicon focus region corresponds to J_0 Bessel function, as shown in Fig.6, with the first minimum at

$$r_{\min} = 0.38\lambda/\theta_c \quad (12)$$

Fig.6

Electric field distribution of axicon-focused linear polarized laser beam.

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 -profiled laser distribution, let us address the diagram presented in Fig.7.

Fig.7

Plasma channel produced by cylindrical shock wave.

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,[30]

$$\mu_{\omega} \approx 0.1 N_e v_{eff} / \omega^2, \quad (13)$$

reaches the inverse length of optical ray propagation across the focal region, $\mu_{\omega} \approx \theta / 2r_{min}$, the input laser radiation is absorbed within the first Bessel maximum.

Note, that partial reflection of the incident radiation from the plasma column is still possible, reducing the efficiency of the laser energy deposition into the optical discharge. However, due to a quadratic dependence of the threshold N_e upon the axicon angle θ (see Eq.(5)), at a reasonably high θ the developed plasma density is several orders of magnitude higher than that required for a waveguiding.

The intense plasma heating results in a local temperature increase to $\sim 50,000$ °K observed as an extended bright spark and known as an "optical breakdown". The proportional adiabatic pressure increase generates a cylindrical detonation wave expanding outwards with a supersonic velocity of ~ 10 km/s. Behavior of such waves is similar to the propagation of high-current discharges or explosive combustion waves and have been extensively studied previously.[30] It is known that a shock wave, propagating in a gas as a supersonic piston, produces a discontinuity of the gas density of much higher amplitude than the ambient gas

density and leaves behind a rarefied channel. Typical distributions of the gas density and temperature in a shock wave are sketched in Fig.7(c). Comparative simulations results for atmospheric high-current discharge are shown also in Fig.8. The superposition of ρ and T distributions produces a characteristic electron density, N_e , distribution shown in Fig.7(d) with a positive gradient $\partial N_e / \partial r > 0$ desired for waveguiding.

Fig.8

Distribution of thermodynamic parameters in a shock wave [31]

Fig.9

Dynamics of electron plasma profile behind laser-produced shock wave[22]

Computational results, obtained for the referred experiment[22] and presented together with the experimental conditions in Fig.9, show resemblance to the above qualitative analysis. The Nd:YAG 1.06- μ m laser beam, focused into a spot with FWHM=25 μ m at the entrance of the miniature "plasma pipe" and with

the radius $\sim 50 \mu\text{m}$ and length 1 cm at an optimum delay time after the initiation of the gas breakdown, has been efficiently transmitted over the pipe a distance corresponding to $24z_0$. Simulations and measurements indicate the presence of a plasma density shell with $\Delta N_e \approx 10^{18} \text{cm}^{-3}$, which is well above the threshold value required by Eq.(7) for a laser beam channeling.

By the nature of the described process, both N_e and ρ have strong radial variations inside a plasma channel. Actually, the density drop is close to the temperature increase, which is between 10-100 times. This fact is important for application of this waveguiding method to laser-driven plasma acceleration. For instance, this means that the plasma waveguide will not be washed out by the guided laser beam with an intensity above the tunneling ionization threshold.

Taking into account the quadratic wavelength dependence for avalanche ionization (Eq.(A7)) and for inverse bremsstrahlung absorption (Eq.(13)), we conclude that the strong energy loading required for shock wave generation may be obtained with CO_2 lasers at much lower gas density than with short-wavelength lasers. That may be beneficial for laser acceleration where low electron scattering in a gas is required. The insensitivity of the waveguiding condition, Eq.(7), upon the λ , presumes that a CO_2 laser as the source of a guided beam will perform as well as the Nd:YAG laser used in the referred experiment.

It is important for this method that the radius of the produced waveguide is much less critical to the laser energy deposited into the optical discharge than one would expect. Let us use the expression for shock wave velocity

$$v_{sw} = \sqrt{\frac{2}{\gamma_0 + 1} \frac{p}{\rho_0}}$$

and the adiabatic equation $p = (\gamma_0 - 1) \chi T \rho_0$, where γ_0 is the adiabatic coefficient, and χ is the specific heat. From these expressions, we derive proportions: $p \sim \mathcal{E} V \sim \mathcal{E} v_{sw}^2$, where V is the volume of the plasma channel and $\mathcal{E}$ is the thermodynamic energy, and ultimately $v_{sw} \sim (\mathcal{E} \rho_0)^{1/4}$. This means that even with longitudinally nonuniform energy deposition into the discharge, as shown in Fig.4, the geometry of the produced plasma channel may be still reasonably regular over a long distance.

To find the design parameters for the experimental demonstration of this method, we should estimate two interrelated parameters. The first is the gas density required for efficient CO_2 laser energy loading into the narrow gas cylinder corresponding to the first Bessel maximum of the axicon-focused beam. The second is the laser energy required to drive a shock wave over the waveguide radius.

To estimate the first parameter, we use Eqs.(12), (13) and $\mu_e \approx \theta_c / 2r_{min}$. From these equations and under the assumption of the complete ionization of the gas in the axicon focal maximum we derive that the required plasma density for efficient laser energy deposition scales as $N_e \sim \omega^{3/2}$. For CO_2 laser radiation and with $\nu_{eff} = 4.4 \times 10^{12} \text{ Hz/atm (hydrogen)}$, we obtain an engineering formula $N_e [\text{cm}^{-3}] \approx 10^{16} \times \theta_c [\text{mrad}]$. Understanding that the laser beam should be focused in a much more narrow region than the ultimately desired waveguide diameter to allow

distance for shock wave development and propagation, we estimate $N_e \approx 10^{18} \text{ cm}^{-3}$ for a waveguide with a radius of $150 \text{ }\mu\text{m}$. Note, that after plasma channel expansion, we get a rarefied axial region with a gas density of 10^{16} - 10^{17} cm^{-3} , that is within the range relevant for plasma-based laser accelerators (see Tables 1 and 2).

To estimate the laser energy required to drive a shock wave, we assume a typical 100-times pressure and temperature jump behind the shock wave and that ~50% of the incident energy is reflected and ~30% of the deposited energy is transformed into the shock wave energy.[31] We find that the total laser energy required to produce a waveguide with a radius of $150 \text{ }\mu\text{m}$ in hydrogen gas with the initial atomic density 10^{18} cm^{-3} is 0.5-1 J per 10 cm of waveguide, which is attainable with the present ATF CO_2 laser (see Appendix B).

2.2.3 Plasma in Hollow Waveguide

The "plasma-in-hollow-waveguide" technique looks relatively simple. However, to our knowledge, this process was not experimentally studied yet. The experimental tests may be performed at the ATF using the now operational 50-ps 20 GW CO_2 laser. Dielectric or metal waveguides may be used for the tests with the threshold of plasma formation ranging, correspondingly, from 0.5 J/cm^2 to 5 J/cm^2 [32]. With the ablation wave propagating inside the waveguide channel with a velocity between 10-100 km/s, the developed plasma layer will not exceed a few micrometers for the time interval corresponding to the laser pulse duration. This situation is different from the considered earlier laser pulse propagating inside a channel with overdense plasma walls for which a strong attenuation after multiple reflections, due to resonance absorption by the plasma waves, has been predicted[33]. The overdense plasma layer with a thickness much less than the laser wavelength will hardly introduce the appreciable losses [34] and the transmission characteristics of a hollow waveguide may be taken close to those known for the low power regime.

It looks that the direct test of this method may be done relatively easily. So, instead of further speculations, we proceed with the essentials of such an experiment.

The requirements of an energy efficient production of a reasonably uniform plasma channel presume that the optical attenuation in the channel should not be high, but also should not be extremely small in order to ensure that the laser energy deposited to the wall is above the ablation threshold. We would choose attenuation at the level of 20-30% over the 10-20 cm of the waveguide length as the optimal figure that it is possible to satisfy with a number of materials.

To estimate the laser flux on the waveguide wall, we may take the Rayleigh length z_0 as a characteristic distance of the interaction of the focused radiation with the cylinder radius of which r_{ch} is equal to w_0 (after passing this distance, laser spot would grow twice in area due to diffraction divergence and, hence, 50% of the laser beam will get in contact with the wall). The CO_2 laser energy required under this approach for plasma ignition inside a dielectric waveguide with $r_{ch}=w_0=50 \text{ }\mu\text{m}$ is just 1.2 mJ, and increases to 35 mJ at $r_{ch}=w_0=150 \text{ }\mu\text{m}$. (Note that the required energy fluence grows as r_{ch}^3 because of

$z_0 \sim w_0^2$.) The 1 J available output energy of the ATF CO₂ laser should be enough to generate plasma inside a dielectric hollow cylinder of 1 mm diameter, or even larger if we choose $r_{ch} > w_0$. Actually, this proportion is a natural requirement in order to obtain a good coupling of laser radiation into the waveguide without a strong sparking at the tip of the waveguide that would block its entrance for the second, delayed laser beam.

After the termination of the laser pulse, the continuing expansion of plasma inside the channel will produce a radial distribution of plasma density required for total reflection of the laser beam that will be injected after a variable delay. While the CO₂ laser looks like the best choice for plasma channel formation, due to its low ablation threshold, the waveguiding conditions produced may be probed with any lasers available at the ATF including a 12-ps Nd:YAG laser or its second and fourth harmonics. As shown above, the waveguiding conditions are supposed to be insensitive to the laser wavelength provided a fixed focus spot size. The change in attenuation and in a spatial mode of the guided beam will serve as a manifestation of the plasma channel formation. The optical delay between laser pulses is determined by the time required for plasma to fill the channel. Among other parameters, it depends upon the laser intensity and the diameter of the channel and is of the order of a nanosecond. Such a delay is easy to set and adjust optically. In order to avoid an additional plasma formation along the axis of the hollow channel, it should be evacuated.

As shown, the experiments may be conducted with the presently operational 20 GW CO₂ and 1-GW Nd:YAG lasers. As the second step, it would be interesting to study the propagation of a 1-TW CO₂ laser beam through the preformed channel. A spliced portion of this beam may be used for plasma channel formation, or the present CO₂ amplifier may still be in use for this purpose.

Finally, we would like to mention again that this method is attractive due to its relative simplicity. Also, we do not envision any particular restrictions for the operating plasma density that may vary from vacuum up to overdense plasma, if required. That means that the hollow waveguide method may be considered for any laser accelerator technique discussed next in Section 3 where the plasma density may vary from $3 \times 10^{14} \text{ cm}^{-3}$ to $1.2 \times 10^{19} \text{ cm}^{-3}$. However, until this method is demonstrated, we can not make any conclusion about its applicability to plasma accelerators. That is why the alternative methods described above should also be considered.

2.3 PROPAGATION OF LASER PULSES IN PLASMA CHANNELS

We conclude Section 2 by reviewing available simulation data on the intense laser pulse propagation in a plasma waveguide. There are several relevant simulation studies done in this field: by T. Katsouleas, et al.[17,33] who considered LWFA in a hollow channel, P. Sprangle, et al.[16,19] who modeled parabolically profiled plasma density channel, and S. Bulanov, et al.[35] who

modeled a channel filled with underdense plasma and with sharp overdense plasma walls.

The concept of the hollow plasma channel[17,33] presumes an ideal cylindrical vacuum tunnel in otherwise uniform underdense plasma. A hollow channel with vertical walls may be considered as an approximation to a dynamic waveguide described in the paragraph 2.2.1.2. In the simulations, the diameter of the channel is assumed to be equal to the plasma wavelength. The remarkable result of this simulation is not just a low-loss propagation of the laser pulse over at least $13 z_0$ distance but also the demonstration of a strong axial field due to a plasma wave excited by the guided laser at the surface of the plasma channel. Characteristic for this field is a high radial uniformity, much better than produced in a standard scheme with a Gaussian laser beam in a uniform plasma. The amplitude of this field along the axis of the evacuated waveguide is just twice below the figure obtained for the uniform plasma.

The same model is partially applicable to other foreseen practical situation when a plasma cloud is developed by laser ablation from cylindrical walls of a solid hollow waveguide. The work of S. Bulanov, et al.[35] may be considered as more direct simulations of such situation. They performed particle-in-cell simulations of the interaction of a short laser pulse with the wall in a narrow cylindrical channel, creation of an electron cloud, excitation of the strong wake field, and the acceleration of charged particles.

Fig. 10

Intensity of laser pulse propagating in a plasma waveguide of a parabolic profile

$$\Delta N_e = \frac{mc^2}{e^2 w_0 \pi} \equiv (r_e w_0^2 \pi)^{-1} \quad [36]$$

Modeling of the intense laser pulse propagating in a parabolic plasma density channel, where $\Delta N_e(r) = (\pi r^2)^{-1}$ and $N_e(0)$ determined from the condition $\omega_0 = \lambda_p$, results in a stable laser pulse amplitude over at least $20z_0$ (see Fig. 10). A periodical modulation of the plasma density due to a plasma wave generation is taken into the account during this simulation.

However, the initial plasma is considered to be totally ionized as behind a shock wave where the plasma density distribution nearly reproduces the gas density profile. That condition is not fulfilled for a plasma developed in a uniform gas by the stationary waveguide method described in paragraph 2.2.1.1. The intense laser pulse, above the tunneling ionization threshold, quickly completes gas ionization washing out the preformed plasma channel. Hence, it is questionable how much a stationary waveguide may be applicable for guiding extremely intense laser radiation.

It would be interesting to consider a combination of two optical guiding mechanisms, preformed plasma channel and RSF. Since the actual laser beam amplitude falls off transversely (e.g., Gaussian beam), i.e., $\partial/\partial r < 0$, same will the relativistic mass of electron due to its quiver motion in the laser field. According to Eq.(1), refractive index will show similar transverse drop. The additional factor responsible for creation of waveguiding conditions for relativistically strong laser beam is the electron plasma density profiling due to the pondermotive expelling of electrons out of the axial region. Analysis of beam envelope equations [18,36] shows that the confinement of the laser beam is possible provided the laser power is above a certain critical value required for RSF, [37]

$$P > P_{cr} = 17.4(\lambda_p/\lambda)^2 [\text{GW}], \quad (14)$$

where λ_p is the plasma wavelength

$$\lambda_p = (\pi c^2 m / e^2 N_e)^{1/2}. \quad (15)$$

RSF does not occur for short pulses $c\tau_L < \lambda_p$. [18] For short pulses, plasma can not collectively respond to modify the refractive index. Estimating the extending of the interaction length due to RSF with longer pulses, we should consider diffraction erosion at the leading front of the pulse, $\tau_{front} \approx \lambda_p/c$, where RSF is not developed yet. [18,19] The erosion front will move inside the pulse with the velocity $v_E = c(\lambda_p/z_0) = c\lambda_p/\pi\omega_0$. Hence, the pulse may experience RSF only over the number of diffraction distances L_{int} not exceeding $c\tau_L/\pi\lambda_p$. We see, that for the efficient RSF condition $\tau_L \gg \lambda_p/c$ should be satisfied.

We may expect that a plasma waveguide preformed by the stationary method will help to compensate for the diffraction divergence of the leading front while the relativistic mechanism will contain the main body of the pulse. Similar approach works with the suggested tailored laser pulse profiles [16,19] where relatively big-spot-size leading portion of the pulse with a long Rayleigh length produces relativistic guiding conditions for a tight focused body of the pulse. The efficiency of this method is illustrated by Fig. 11 where comparative results for different waveguiding methods are given.

We shall mention here, that because of a λ_p -periodic perturbations of electron density in a plasma wave, the RSF effect is also spatially periodical in the

relativistic frame that moves with the laser pulse. This results in a periodic modulation of the long, intense laser pulse. We will see later the significance of that effect for plasma accelerators.

We shall understand that a theoretical study of a propagation of the intense laser pulses in preformed plasma channels is presently at its early stage. More rigorous simulations are under way revealing complicated features of the process. Sprangle, et al.[36] predicted a nonsymmetric evolution of the laser beam envelope and centroid called "hose modulation instability". The cause of this instability is coupling of the laser pulse with radial component of the induced wake field. Such instability may appear in preformed plasma channels too.[38] The suggested stabilization method consists in detuning plasma frequency (density) along the laser beam path.

A wake breakout due to Raman scattering and a filamentation of a relativistically strong laser beams has been predicted.[20,39] On the other hand, it was shown that a magnetic interaction of self-focusing filaments results in their coalescence and the suppression of initial beam instability.[21]

While further theoretical study of plasma waveguiding is required, the first modeling results and experimental demonstration prove that this approach is viable and needs to be further experimentally persuade.

Fig.11
Comparative simulations for different waveguiding techniques [16].

Section 3

Electron Acceleration by Channeled Picosecond CO₂ Laser Beams

We start this section getting an understanding of the basic principles of plasma wave generation and its properties that are general for all plasma based laser accelerator schemes. This discussion is based on T.Tajima and J.M. Dawson's pioneering paper on Laser Electron Accelerators.[7]

When an electromagnetic wave packet travels through plasma in the z-direction it sets electrons into transverse oscillation. Actually, the plasma may be produced by the same light pulse. Picking up an energy

$$W_{osc} = \frac{m}{2} \left\langle \left(\frac{\partial r}{\partial t} \right)^2 \right\rangle = e^2 E_L^2 / 2m\omega^2$$

from the light wave, the electron must also to pick up the light wave momentum in z-direction, $\langle \Delta p_z \rangle = W_{osc} / c$. Here W_{osc} is called the pondermotive potential and E_L is the electric field of the laser field. After the light pulse passage, the electron will be displaced in the z-direction and the electrostatic potential produced by the space charge separation will pull the electron back. Thus, plasma oscillation with a characteristic frequency $\omega_p = 2\pi c / \lambda_p$ is set up, where λ_p is defined by Eq.(15).

As long as the starting phase of the collective electron oscillation corresponds to the laser pulse position, we conclude that the phase velocity of the plasma wave is equal to the group velocity of light in plasma which is equal to $v_g = cn$, where $n = (1 - \omega_p^2 / \omega^2)^{1/2}$ is known as a plasma refraction.

Once generated, the plasma wave stays for a relatively long time. The measured plasma wave damping time due to electron ion collisions under the conditions of the UCLA experiment[10] is $5 \times 10^{-4} \omega_p$. This means that a relatively long electron bunch, not restricted to the laser pulse duration, may be accelerated.

Moving together with the plasma wave with a velocity close to v_g , an externally seeded electron will be accelerated by the field E_a over many plasma periods. The condition for this is $\beta = v_g / c$ and hence $\gamma = \omega / \omega_p$.

To estimate the magnitude of the electrostatic field due to charge separation in the plasma wave, which is used in plasma accelerators as a longitudinal accelerating field E_a , we should find the amplitude of this oscillating motion. After double time-integration of the equation

$$\frac{\partial^2 z}{\partial t^2} = \frac{eE_a}{m} \quad \text{with assumed } \Delta z = \Delta z^{max} \sin \omega_p t, \quad \text{we get } \Delta z^{max} = eE_a / m\omega_p^2.$$

The maximum amplitude of this oscillation is set by the wave-breaking limit that states that the oscillation amplitude of the electron should not exceed the plasma wavelength, $\Delta z^{max} \leq \lambda_p = 2\pi c / \omega_p$. Hence, at the wave breakdown limit, $E_a = 2\pi mc \omega_p / e$ or, using Eq.(15) for λ_p ,

$$E_a[\text{V/cm}] = \sqrt{N_e} [\text{cm}^{-3}] \quad (16)$$

For partial electron density modulation in a plasma wave, Eq.(16) takes the form

$$E_a = \delta \sqrt{N_e}, \quad (17)$$

where $\delta = \Delta N_e / N_e$.

In the case of relativistic oscillations in a strong laser field, the increase of the electron mass by $\gamma_{\perp}$ will result in an additional factor $E_a \sim \sqrt{\gamma_{\perp}}$

We see that as soon as the plasma wave is set, its three parameters, N_e , δ , and $\gamma_{\perp}$ determine E_a . In plasma based laser accelerators these parameters are ultimately related to the characteristics of a laser driver and a particular choice of the plasma wave excitation method.

Use the large longitudinal ponderomotive force (radiation pressure) of light to excite plasma waves

Three possibilities:

I. Use a single intense pulse

Laser Wakefield Accelerator (LWFA)

II. Beat two pulses together, i.e., a train of pulses

Plasma Beat Wave Accelerator (PBWA)

III. A long pulse would undergo an instability evolves to

Self-Modulated LWFA

Fig.12 Methods of plasma wave generation [39]

It is evident that the most efficient way to pump the oscillation is to apply the external force in resonance with the oscillator eigenfrequency. This is the idea of a laser beat wave accelerator, LBWA, where two monochromatic optical signals produce amplitude ripples at the beat frequency equal to the plasma frequency, $\Delta\omega = \omega_1 - \omega_2 = \omega_p$.

In the case of a quasimonochromatic laser pulse, plasma oscillation is generated most efficiently if the laser pulse duration is half of the plasma period. Such a technique used in a standard laser wake field accelerator (standard LWFA) is simpler but less energy efficient than the LBWA.

The third process, self-modulated LWFA, is observed at a high laser intensity that satisfies RSF conditions and shares features of both previously described processes. It starts as a standard LWFA but with a laser pulse much longer than the plasma period. A plasma wave generated by the leading portion of the pulse periodically modulates the main body of the pulse due to the relativistic focusing and defocusing. As a result, the pulse acquires ripples that automatically match the periodicity of the plasma wave, and the process continues with the high efficiency typical for LBWA.

Fig.12 gives a graphic overview of the considered methods of laser plasma acceleration.

Throughout the Section we compare a CO₂ laser as the accelerator driver with the presently more common Nd:YAG picosecond lasers. We consider the possibility of demonstrating plasma acceleration over an extended distance of several Rayleigh lengths when a tightly focused picosecond CO₂ laser beam used as a driver for a plasma accelerator is guided along the preformed plasma channel as described in Section 2.

3.1 LASER BEAT WAVE ACCELERATOR (LBWA)

In LBWA, the plasma waves are generated by coupling of two copropagating laser beams with frequencies ω_1 and ω_2 . The pondermotive force

$$F = -\frac{\omega_p^2}{\omega_1 \omega_2} \nabla \left\langle \frac{|E_{L1} + E_{L2}|^2}{8\pi} \right\rangle,$$

where E_{L1} and E_{L2} are electric fields of the two laser beams, causes plasma electrons to bunch periodically along the axis of the laser beams propagation as shown in Fig.13. Under the resonance condition $\Delta\omega = \omega_1 - \omega_2 = \omega_p$ the plasma wave amplitude $\delta = \Delta N_e / N_e$ initially grows linearly with time according to the relation

$$\frac{1}{\omega_p} \frac{\partial \delta}{\partial t} = \frac{1}{4} a_1(t) a_2(t),$$

where $a_{1,2}$ is the unitless laser strength parameter defined as the normalized amplitude of the laser vector potential (or normalized oscillatory velocity of an electron in the laser field) as

$$a = v_{osc}/c \approx A_0/mc^2 \approx eE_L/m\omega c \quad (18)$$

with the corresponding engineering formula

$$a = 0.3 E_L [\text{TV/m}] \lambda [\mu\text{m}]. \quad (18a)$$

and E_L related to the laser intensity I_L by

$$E_L = (2I_L/\epsilon_0 c)^{1/2}, \quad \text{or} \quad E_L [\text{TV/m}] = 2.6 \times 10^{-9} I_L^{1/2} [\text{W/cm}^2]. \quad (19)$$

Fig. 13

Schematic diagram of the beatwave, ponderomotive force, concentrations of the positive and negative charges, the associated electric fields, electron density distribution, and the ponderomotive wave in the plasma [11].

Oscillating plasma electrons relativistically grow in mass and the plasma frequency no longer matches $\Delta\omega$. This dephasing causes the plasma wave amplitude growth to slow and then saturate. The saturated wave amplitude is given by

$$\delta_s = \left[\frac{16}{3} a_1(t) a_2(t) \right]^{1/3}. \quad (20)$$

The saturated longitudinal electric field amplitude given by Eq(17) with $\delta=\delta_s$ is the maximum acceleration field attainable with LBWA. The time to saturation is determined from

$$\frac{\omega_p}{4} \int_0^{\tau_s} a_1(t) a_2(t) dt = \delta_s.$$

Assuming stationary amplitudes $a_{1,2}$, we get

$$\tau_s = 1.75 / \omega_p [a_1 a_2]^{2/3}. \quad (21)$$

For maximum plasma wave amplitude, the time to saturation should match to the laser pulse duration.

An important feature of plasma-based laser accelerators is the synchronism between the group velocity of the laser pulse and the phase velocity of the plasma wave. The injected electrons should also stay in synchronism with the plasma wave, and they are accelerated by the electrostatic field until they outrun the wave. The dephasing distance is[7]

$$L_{ph} = \frac{1}{\pi} \lambda_p \gamma^2 = \frac{1}{\pi} \frac{\lambda_p^3}{\lambda^2} \quad (22)$$

and the maximum energy gain is

$$\Delta W = 4 \delta_s \gamma^2 m c^2. \quad (23)$$

Being highly efficient in transforming the laser electromagnetic field into the plasma wake field, the LBWA method was used in one of the most successful laser acceleration experiments so far, when $\Delta W=18$ MeV was demonstrated.[10] In this experiment, two CO₂ laser beams with wavelengths $\lambda_1=10.59$ μm and $\lambda_2=10.29$ μm have been focused into a spot of $w_0=150$ μm , producing intensities of $I_1=2.8 \times 10^{14}$ W/cm² and $I_2=0.7 \times 10^{14}$ W/cm². The saturated wave amplitude corresponding to these laser parameters is $\delta_s=0.37$. This would develop, at the measured plasma density $N_e=6 \times 10^{15}$ cm⁻³ and the corresponding $\lambda_p=420$ μm , the maximum attainable acceleration field $E_a^{max}=2.8$ GV/m (by Eq.(17)). The plasma amplitude measured by Thompson scattering was in the range of $\delta=0.15-0.3$, and the experimental average acceleration of 1.8 GV/m correlates reasonably well with the above estimate. The acceleration distance was limited to 1 cm by the laser beam diffraction range determined by the formula

$$L_{int} = \pi z_0 = \pi^2 w_0^2 / \lambda, \quad (24)$$

We refer to Table 1 for a comparison of the projected picosecond 1 TW CO₂ laser with alternative LBWA laser drivers. We assume that the total 1 TW laser power is equally distributed between two beams with wavelengths $\lambda_1=10.6$ μm and $\lambda_2=10.3$ μm . As comparative examples, we use the UCLA experiment (column 1),[10] its extension as proposed at the Advanced Accelerator Concepts

Workshop'92 (column 2),[9] and a Hybrid Wakefield/Beatwave Accelerator (column 3)[33].

Table 1.
LBWA Prospective Comparative Characteristics

	UCLA	AAC'92	Hybrid	A T F	
	CO ₂	Ti-Sapph	Nd:YAG	CO ₂	CO ₂
Laser Parameters					
Wavelengths λ [μm]	10.59, 10.29	1.053, 1.086	1.05, 1.06	10.59, 10.29	10.59, 10.29
Pulse length τ_L [ps]	300	4	1.4	10	10
Total power P [TW]	0.25	2.5	10	1	1
Focal spot radius, w_0 [μm]	150	90	50	50	150
Total peak intensity I [W/cm ²]	3.5×10^{14}	10^{16}	1.2×10^{17}	1.2×10^{16}	1.2×10^{15}
Laser field, E_L [TV/m]	0.05	0.26	0.9	0.28	0.09
Unitless laser strength (each beam)	0.17, 0.07	0.06	0.2	0.6	0.2
Wakefield Parameters					
Plasma density, N_e [cm ⁻³]	9×10^{15}	9×10^{17}	10^{17}	9×10^{15}	9×10^{15}
Plasma wavelength λ_p [μm]	330	33	100	330	330
Saturated plasma wave amplitude	0.4 0.15-0.3*	0.27	0.6	1.25	0.6
Acceleration gradient E_a [GeV/m]	3, 1.8*	25	19	12	6
Interaction length, $L_{int} = \pi z_0$ [cm]	2.2	8	2.5	0.25	2.2
Phase detuning length L_{ph} [cm]	11	1	32	11	11
Energy gain (without channeling), ΔW [MeV]	30, 18*	250	200	20	60
Energy gain (with channeling), ΔW [MeV]	300	250	>1000	>1000	600
Electron Beam Parameters					
Initial Energy [MeV]	2	4	?	50	50
Current [A]	0.2	300	?	100	100
Pulse length	10	4	?	12 ps	12 ps
Focused beam radius [μm]	130	?	?	100	100
Number of electrons trapped	10	?	?	10^9	10^9

* - Experiment

If we compare the UCLA and ATF lasers focused into the same $w_0=150$ μm spot (columns 1 and 5), we see that the 4 times higher ATF laser power ultimately results in a two times higher acceleration. This will be attained at ~ 10 times less energy loading that greatly relieves optics damage problems.

It is important for LBWA scheme to have a plasma frequency and hence plasma density adjusted to the beat wave frequency with the accuracy $100\% / (\text{Number of growth cycles})$. E.g., under the UCLA experimental conditions, the number of cycles during the plasma wave growth is ~ 33 giving the required plasma uniformity at the level of 3%. This requirement may not be easy to satisfy when plasma density is spatially profiled for waveguiding. Using a short-pulse, high-intensity laser helps to relieve this constraint. By Eq(22), the acceleration length limited by the dephasing distance is $L_{ph}=11$ cm. With $\delta_s=0.6$ and $E_a^{max}=6$ GV/m, $\Delta W \approx 600$ MeV.

A problem with the AAC'92 proposal as shown in column 2 is a relatively short phase detuning length. That is why the potential of this scheme toward a 1 GeV demonstration is questionable.

Comparing columns 3 and 4 we note that being focused into the same $w_0=50$ μm spot a 1 TW CO_2 laser develops a high accelerating gradient close to that produced with a 10-TW Nd:YAG laser. The required resonant plasma density is 10 times lower for CO_2 . Because of a high diffraction divergence at such tighter focusing, the CO_2 laser will perform really well only in a waveguide where as high as 1 GeV net acceleration may be demonstrated.

3.2 LASER WAKE FIELD ACCELERATORS (LWFA)

3.2.1 Standard LWFA

In the standard LWFA scheme,[7,8] a short and intense laser pulse propagating through an underdense plasma pondermotively expels electrons leaving behind a periodic space charge wave (wake) that propagates with the group speed of light behind the laser pulse. The wake field strength depends upon the laser intensity and how well the laser pulse length matches the plasma wavelength λ_p .

For the resonance condition when

$$c\tau_L = \lambda_p / 2 \quad (25)$$

or

$$N_e = \pi m / 4c^2 \tau_L^2, \quad (25a)$$

the accelerating wake field is related to the laser field by the ratio[40]

$$E_a = (\pi^2 m c^2 / e) a_L^2 / 4 \lambda_p (1 + a_L^2 / 2)^{1/2}, \quad (26)$$

where a_L is defined by Eq.(18).

The corresponding engineering formula for the efficiency η of transforming a transverse laser field into the accelerating longitudinal wake field is

$$\eta = E_d/E_L = 1.6 \times 10^{-11} N_e^{1/2} [cm^{-3}] \lambda [\mu m] a_L / (1 + a_L^2/2)^{1/2} \quad (27)$$

It follows from Eq.(27) that the efficiency η increases proportionally to $I_L^{1/2}$ at low laser intensity ($a_L \ll 1$), then reaching the saturation at the level of

$$\eta_s = 2.25 \times 10^{-11} N_e^{1/2} [cm^{-3}] \lambda [\mu m] \quad (28)$$

We see that the increase of λ results in a proportional increase of η , provided other parameters are fixed. So far, one of the advantages of the Nd:YAG lasers (or other picosecond short-wavelength lasers) as the LWFA drivers over conventional subnanosecond CO₂ lasers was due to the proportionality $\eta_s \sim \lambda/\tau_L$ (see Eqs.(28) and (25a)). As a result, the advantage of CO₂ lasers in longer λ was greatly outweighed by much longer τ_L . With a long τ_L , the resonance N_e was too low to be of any practical interest. With the development of a picosecond CO₂ laser, there is for the first time the possibility to use a long-wavelength laser driver for LWFA. At the resonance conditions with $\tau_L = 3$ ps and corresponding $N_e = 3 \times 10^{14} cm^{-3}$, we get by Eq.(28) $\eta_s = 0.04\%$ for $\lambda = 1 \mu m$ (Nd:YAG laser) and $\eta_s = 0.4\%$ for $\lambda = 10 \mu m$ (CO₂ laser). The condition of $a_L \gg 1$ to reach the saturated efficiency is also easier to satisfy with a CO₂ laser, as follows from Eq.(18a).

One may argue that the λ -proportional diffraction divergence of the laser beam (see Eq.(6)) and the resulting field limitation may outweigh the advantage of an ncrease in a_L with λ . Indeed, when a laser beam is focused with a lens, the produced spot size is proportional to λ . However, when a practical LWFA scheme is considered, the goal is to focus the laser beam not to the λ -limited diffraction extremes but to the diameter of the electron beam, which is hard to imagine being much smaller than $\sim 100 \mu m$ over an appreciably long acceleration distance. There should not be any problem to focus a CO₂ laser beam into such a spot.

To understand better the specifics of a picosecond CO₂ laser as a LWFA driver, it is instructive to compare it with the 2 TW Nd:YAG laser used for the acceleration experiment at NRL (see Table 2, columns 1 and 3). Focusing a CO₂ laser beam of 1 TW peak power to a spot with a radius of $w_0 = 50 \mu m$ results in the intensity of $I_L = 1.2 \times 10^{16} W/cm^2$, transverse electric field $E_L = 280$ GV/m (by Eq.(19)), $a_L = 0.9$ (by Eq.(18a)), and with $N_e = 3 \times 10^{14} cm^{-3}$, the acceleration gradient $E_a = 620$ MeV/m (by Eq.(27)). Note that because of the λ -dependence of the laser strength parameter, the CO₂ laser, in spite of being much less tightly focused, is characterized by somewhat higher efficiency. Due to short Rayleigh ranges, the acceleration without beam channeling is meaningless in both cases considered.

Talking about plasma channeling, we should admit that generation of a plasma channel of a $10 \mu m$ radius looks less technically feasible than a $50\text{-}\mu m$ channel. Note also that an attempt to use a less tightly focused $1\text{-}\mu m$ beam results in a dramatic drop of the acceleration gradient compared with the CO₂ case. This is why we extend our estimates to acceleration in the assumed low-loss plasma waveguide only for ATF conditions.

For plasma acceleration in a preformed plasma channel the Rayleigh length restriction on the interaction distance is not a limit any more and other factors should be considered when estimating the efficient propagation distance of

an intense laser beam in a plasma waveguide. One of them is pump power depletion due to the inverse bremsstrahlung enhanced by the resonant absorption in a plasma wave. The expression for the depletion length L_d is [37]

$$L_d = c\tau_L/\eta^2. \quad (29)$$

After passing this distance, the energy in the trailing wake field becomes comparable with the initial laser energy. For $\tau_L=3$ ps and $\eta=0.22\%$ characteristic of standard LWFA driven by a 1 TW CO₂ laser, $L_d=200$ m.

The phase detuning length L_{ph} is as previously, the distance over which a relativistic electron outruns the wake field of the laser pulse by $\lambda_p/2$ and no longer gains energy. The expression for L_{ph} in LWFA is [8]

$$L_{ph} \approx 2\lambda_p^3/\lambda^2(1+\lambda_p^2/4w_0^2), \quad (30)$$

and for $\lambda=10.6$ μm , $\lambda_p=2$ mm, $w_0=50$ μm , we get $L_{ph} \approx 40$ cm.

In the case of a standard LWFA in a plasma channel, the maximum length of the acceleration stage will be the least value among L_{ph} , or L_{ch} - the length of the plasma channel. For example, with a 30 cm long plasma waveguide, the maximum predicted acceleration with a 1 TW CO₂ laser used in a standard LWFA scheme under the conditions specified above is ~ 200 MeV.

3.2.2 Self-Modulated LWFA

In the proposed self-modulated LWFA scheme [40], enhanced acceleration is achieved via resonant self-modulation of the laser pulse. This occurs when the laser pulse extends over several plasma wavelengths, $c\tau_L \gg \lambda_p$, and the peak laser power satisfies Eq.(14) that is $P \geq P_{cr}$. Fig.14 presents results of modeling of the self-modulation effect.

In the self-modulated regime, acceleration is enhanced for four reasons, assuming fixed laser parameters:

- a) Since smaller λ_p and, hence, higher N_e is required, the wake field is increased $E_a \sim N_e^{1/2}$.
- b) The resonant mechanism excites a higher amplitude plasma wave in comparison with the standard LWFA.
- c) Since $P \geq P_{cr}$, RSF further enhances laser intensity, increasing a_L .
- d) A portion of the laser pulse will remain guided over several Rayleigh lengths, extending the acceleration distance.

According to simulations for the proposed 100 MeV self-modulated LWFA demonstration experiment at NRL [40], an increase of N_e from 10^{17} cm⁻³, as required to satisfy the resonance condition for a standard LWFA in Eq.(25), to as high as 10^{19} cm⁻³ results in the increase of the accelerating wake field from 6

GV/m to 300 GV/m. (Note, that under the proposed experimental conditions, $w_0=10 \mu\text{m}$ and $E_L=2 \text{ TV/m}$.)

Fig. 14
Self-modulation of relativistically strong laser pulse [16]

Comparing a CO_2 laser with the short-wavelength ($\lambda=1.054 \mu\text{m}$) laser driver used in the NRL experiment (Table 2, columns 2 and 4), we see again that the long wavelength of a CO_2 laser helps to satisfy condition $P \geq P_{cr}$ for a self-modulated LWFA. In order to satisfy this condition with a 1-TW CO_2 laser, the plasma wavelength should be $\lambda_p \leq 80 \mu\text{m}$, which corresponds to $N_p \geq 1.7 \times 10^{17} \text{ cm}^{-3}$. Two orders of magnitude reduction in plasma density greatly relieves the problem of electron beam scattering that could be an issue for prospective accelerators based on the self-modulated LWFA technique.

The direct application of an analytical approach valid for a standard LWFA (Eqs.(26)-(28)) to the self-modulated case, not taking into the account resonance effects, gives at least five times less accelerating gradients than the simulations[40]. Actually, according to the simulations, the wake field reaches the level determined by Eq.(16) that would be characteristic for LBWA with a strong laser driver. Because of a high laser strength parameter, in the ATF case we face a similar situation. Using Eq.(16) for the self-mod. ATF scheme, we may expect a net gain of $>50 \text{ MeV}$ even without channeling.

Though the acceleration gradient in the example given in Table 2 column 4 for a CO_2 laser is not as impressive as the mentioned above from the NRL proposal, we attain it with much weaker focusing, which is more compatible with a realistic e-beam size and allows waveguiding conditions to be maintained as specified in Section 2.

Table 2
Standard and Self-Modulated LWFA
Prospective Comparative Characteristics

	N R L		A T F	
	Stand.	S-Mod.	Stand.	S-Mod
Laser Parameters				
Wavelength λ [μm]	1.054	1.054	10.6	10.6
Energy [J]	1.5	1.5	3	10
Pulse length τ_L [ps]	0.75	0.75	3	10
Power P [TW]	2	2	1	1
Focal spot radius, w_0 [μm]	10	10	50	50
Peak intensity I [W/cm^2]	0.6×10^{18}	0.6×10^{18}	1.2×10^{16}	1.2×10^{16}
Laser field, E_L [TV/m]	2	2	0.28	0.28
Unitless laser strength	0.6	0.6	0.9	0.9
Wakefield Parameters				
Plasma density, N_e [cm^{-3}]	5×10^{15}	1.2×10^{19}	3×10^{14}	1.7×10^{17}
Plasma wavelength λ_p [μm]	500	10	2000	80
Efficiency $\eta = E_a/E_L$ [%]	0.065	>3.2	0.22	>5.4
Acceleration gradient E_a [GeV/m]	1.3	>300*	0.62	>40
Interaction length, $L_{int} = \pi z_0$ [cm]	0.1	0.1	0.25	0.25
Pump depletion length, $L_D = c\tau_L/\eta^2$ [cm]	6×10^4	24	2×10^4	10^3
Phase detuning length L_{ph} [cm]	40	0.4	40	0.6
Energy gain (without channeling), ΔW [MeV]	0.6	>100*	0.7	>50
Energy gain (with channeling), ΔW [MeV]	?	?	~200	>200
Electron Beam Parameters				
Initial Energy [MeV]	1	1	50	50
Current [A]	10	10	100	100
Pulse length	50 ns	50 ns	12 ps	12 ps
Focused beam radius [μm]	100	100	100	100
Number of electrons trapped	10^5	10^5	10^9	10^9

* -Simulation

Finally, we estimate an expected net acceleration ΔW in a self-modulated LWFA scheme under wavequiding conditions. To avoid the complicated subject of a plasma channel wash-out due to excessive ionization by the accelerating laser

pulse, we consider a gas density waveguide produced by the shock wave method described in paragraph 2.2.1.2. Due to the gas rarefaction behind the shock wave, even a complete gas ionization that would be observed with the specified laser intensities does not effect waveguiding conditions.

Estimating the physical limitations on the efficient interaction length for self-modulated LWFA, we still use Eq.(30) for the phase detuning length, L_{ph} . With $\eta=5\%$, $\lambda_p=80\text{ }\mu\text{m}$, and $w_0=50\text{ }\mu\text{m}$, we get $L_{ph}=6\text{ mm}$ and $\Delta W\approx 200\text{ MeV}$. We see that a short dephasing time is really a severe restriction for a self-modulated LWFA. We also have a similar situation for the NRL case where $L_{ph}=4\text{ mm}$. This problem is waiting for a solution. For example, it may be interesting to explore the possibility to slow down the electron longitudinal motion in a wiggler. Other previously suggested phase matching methods include: plasma waveguide with a properly adjusted width,[41] and the oblique side injection of the laser beam to the direction of the electron beam.[42]

3.3 Inverse Cherenkov Accelerator

In the present section we consider the possibility of using plasma waveguide concepts discussed above to improve the performance of the Inverse Cherenkov Accelerator (ICA), which is now under experimental test at the ATF.

With a radially polarized laser beam, the axicon focused radiation has a sharp interference maximum of the longitudinal electric field at the axicon axis. However, as shown in Section 2, the much stronger radial component of the laser field peaks along the cylindrical surface concentric to the axis. If the laser beam is intense enough to produce an appreciable gas ionization at the position of this interference maximum, the developed plasma may screen the e-beam propagating along the axicon axis from the incoming laser beam precluding acceleration. This effect is similar to reflection of oblique incident rays inside a plasma waveguide. However, in the present case we consider rays external to the plasma cylinder. It has been calculated, that this effect may limit the acceleration gradient attainable in an ICA driven by a CO_2 laser to 300-600 MeV/m.[43]

Another well recognized adverse effect due to gas filled into the ICA interaction cell is electron scattering described by formula[44]

$$\Delta\theta_{1/e} = \left(\frac{W_s}{W}\right) \left(\frac{z}{L_R}\right)^{1/2} \left[1 + 0.1 \log_{10} \left(\frac{z}{L_R} \right) \right], \quad (31)$$

where $\Delta\theta_{1/e}$ is the angular spread of the e-beam, W is the mean electron energy (MeV), $W_s=19.7\text{ MeV}$ 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 $L_R=7\times 10^5[\text{cm}]/p[\text{atm}]$. The result of gas scattering is the emittance growth of the e-beam and reduced acceleration efficiency due to a bad overlap of the expanded e-beam with the narrow interference maximum of the longitudinal component of the axicon focused laser field. A simplified formula for the e-beam expansion due to multiple scattering

$$\Delta r(z) = \frac{2}{3} \frac{W_s}{W \sqrt{L_R}} z^{3/2} \quad (32)$$

indicates that under the conditions of the ATF ICA experiment (2 atm of hydrogen gas) the e-beam expansion become appreciable after traveling a distance of ~10 cm.

First, let us address a question: is it possible to relieve the described problems of gas breakdown and multiple electron scattering for the ICA scheme by producing a narrow rarefied gas channel along the axis of the e-beam propagation. Such channel may be produced by the shock wave method described in paragraph 2.2.1.2. Under proper laser energy loading into the optical discharge, the produced shock wave channel may be several millimeters in diameter and with an order of magnitude gas density drop at the axis. As a result of the density drop, the reduced electron scattering and higher optical breakdown threshold for the accelerating laser beam could be expected.

However, there are limitations to utilizing this approach. Due to optical refraction at the interface of the undisturbed high-density gas and low-density channel, the inclination of the optical wavefront to the axicon axis will be reduced nearly proportionally to the square root of the density drop in the channel. As a result, the proportion E_a/E_r and hence the ICA efficiency will be reduced. The increase of the efficient interaction range due to a reduced e-beam scattering may not compensate for this reduction.

There is another way envisioned to improve the ICA using a waveguiding plasma channel for laser beam recycling. In that case, the axicon focused beam is introduced inside the preformed plasma channel. In order to satisfy the Cherenkov condition, it is preferable to use a plasma channel with a uniform gas density produced by the stationary method described in Section 2.2.1.1. This is actually an extension of a similar method for laser beam recycling with sapphire waveguides considered by STI Optonics [45] and, before it, for the ATF IFEL experiment.[4] In the case of a plasma waveguide, a drop of the refractive index near the plasma wall, as well as a possible change of a phase velocity and mode structure, should be taken into account when considering application of this method for the ICA experiment, where Cherenkov phase-matching conditions between the electron bunch and laser radiation shall be satisfied.

Section 4

CONCLUSIONS

CO₂ lasers are potentially attractive as laser accelerator drivers because of the 100 times stronger pondermotive action of its radiation compared with more extensively used 1- μ m lasers. Note that the pondermotive action is foundation of such key processes in plasma-based accelerators as avalanche and tunnel ionization, relativistic self-focusing, and plasma wake excitation. Being potentially scalable to high energies and high repetition rates CO₂ lasers may be attractive as next-generation particle accelerator drivers.

Despite this advantage, CO₂ lasers were not specified so far for the ultra-high acceleration experiments (0.1-1 GeV) for two reasons: relatively long, typically of the order of 1 ns pulse duration, and a λ -proportional diffraction divergence that sets a short Rayleigh interaction range.

The terawatt-class picosecond CO₂ 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, it presents new opportunities in laser acceleration study. For instance, Because of the short pulse duration the ATF CO₂ laser presents for the first time an opportunity to study a laser wake field accelerator scheme in a long-wavelength spectral region. Comparisons with the existing proposals in this field show that the long-wavelength approach is quite competitive and introduces certain advantages that are worth exploring.

The diffraction problem will be relieved by the plasma waveguiding considered here. Actually, this problem is general for most of the laser-driven accelerator schemes. We show that waveguiding in a plasma channel is insensitive to the laser wavelength and should work for a CO₂ laser as well as for Nd:YAG lasers. On the other hand, because of the above mentioned features, the CO₂ laser is also a good choice as a driver to produce a plasma channel. It is well known that less laser power and/or lower gas pressure is required for a gas breakdown when λ is increased.

We believe that the proposed studies of a laser acceleration in a plasma waveguide will be a good addition to the present ATF experimental program. The presented analysis shows that these studies may lead to a 100 MeV and even 1 GeV demonstration in a single compact acceleration stage. To specify the design configuration and parameters for the prospective accelerator driven by the terawatt picosecond CO₂ laser, dedicated simulations and preliminary waveguiding experiments within the present ATF capabilities would be highly recommended.

Appendix A

GAS IONIZATION BY IR RADIATION

Gas ionization by laser irradiation is a process responsible for plasma formation in considered herein laser-driven particle accelerators. When relatively long-wavelength CO₂ laser radiation is used, two ionization mechanisms, avalanche and tunneling, play the dominant role. Probabilities and laser power thresholds for both processes are discussed and computed below. All quantitative results are presented for hydrogen gas.

A.1 Avalanche Ionization

Similarly to electric gas discharges, the optically induced gas breakdown under laser irradiation of a moderate intensity (laser electric field is less than intra-atomic field) is produced via a cascade (avalanche) ionization when free electron acquires energy from the laser electromagnetic field via elastic collisions with neutral atoms.[46] After several collisions it may obtain enough energy to ionize the atom and create a free electron of the second generation. This process may continue until the gas breakdown, depending upon the laser pulse duration, τ_L , and intensity I .

To initiate the avalanche, existence of primary free electrons is necessary. Assume that the primary free electrons emerge from impurities with lower ionization potential or via the tunneling ionization. These free electrons exposed to the laser electromagnetic field oscillate at laser frequency. Energy accumulation by the electron via elastic collisions with neutral molecules is $dW/dt = v_{\text{eff}} W_{\text{osc}}/2$, where W_{osc} is a pondermotive potential given by

$$W_{\text{osc}} = e^2 E_L^2 / 2m\omega^2 \quad (\text{A1})$$

and v_{eff} is the effective electron-atom momentum transfer collision frequency, $v_{\text{eff}} = N_m v \sigma$, N_m - gas density, v - electron speed and σ - elastic scattering cross-section. Using

$$I = (1/2) \epsilon_0 c E_L^2, \quad (\text{A2})$$

we obtain

$$dW/dt = (e^2 / 2 \epsilon_0 c m \omega^2) I v_{\text{eff}} \quad (\text{A3})$$

In order to ionize, free electron kinetic energy should reach a value of $W = 2U_0 + U_i$, where U_0 is the initial secondary electron mean energy and U_i is the ionization potential of the medium. Disregarding electron losses to molecular excitation, recombination and diffusion (that is close to be the case for fast avalanche by intense picosecond laser pulses), the energy conservation requires

$$(U_0 + U_i) dN_e/dt = N_e dW/dt. \quad (\text{A4})$$

After integrating Eq.(A4) over the laser pulse duration assuming Gaussian shaped pulse

$$I = I_0 \exp[-(2\Delta t/\tau_L)^2], \quad (A5)$$

we may relate laser and plasma parameters as

$$\ln[N_e(\tau)/N_e(0)] = \pi^{1/2} e^2 v_{eff} \tau_L I_0 / 4 \epsilon_0 m c \omega^2 (U_0 + U_i). \quad (A6)$$

Setting $N_e(\tau)/N_e(0) \approx 10^{14}$ as the condition for the gas breakdown, and $U_0 \approx U_i$ according to a momentum conservation with angular averaging, the gas breakdown threshold intensity is

$$I_{th} = 140 \epsilon_0 c U_i m \omega^2 / \tau_L e^2 v_{eff} \quad (A7)$$

We see that laser wavelength λ and pulse duration τ_L , as well as the gas pressure p (v_{eff}) and ionization potential U_i , are the major factors in determining the threshold of the avalanche breakdown.

Taking $v \approx 1.6 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1}$ for H_2 [47], we obtain $v_{eff} = 4.4 \times 10^{12} \text{ Hz/atm}$. Ultimately, the intensity threshold for the avalanche breakdown produced by CO_2 laser pulse in hydrogen with $U_i = 15.4 \text{ eV}$ will be

$$I_{th} \approx 2.2 \times 10^{13} / p \tau_L, \quad (A8)$$

where τ_L is in psec, p is the gas pressure in atm and I_{th} in W/cm^2 .

A.2 Tunneling ionization

At a high laser intensity ($I \geq 10^{13} \text{ W/cm}^2$) attainable with short picosecond pulses, tunneling and multiphoton ionization become the main mechanisms of a gas breakdown. The intensity threshold, I_{th} , for these processes depends on the laser wavelength and the ionization potential of the medium. The magnitude of I_{th} is not much critical to a pulse duration and practically does not depend upon the gas pressure.

The tunneling and multiphoton ionization probabilities are both described by one general Keldysh formula[48] but under different conditions for the parameter $\gamma = \omega(2mU_i)^{1/2}/eE_L$.

For $\gamma \gg 1$ ionization can be described as a multiphoton process through which a valence electron can escape from the atom by simultaneously absorbing several photons. Because of a high proportion between the ionization potential of any atom to the 10- μm radiation quantum, the multiphoton ionization is least likely to occur with the CO_2 laser light, and the tunneling process is prevailing at the strong irradiation.

For $\gamma \ll 1$ the ionization can be described as a tunneling process which happens in the strong-field, low-frequency limit. Under the $\gamma \ll 1$ limit (laser pulse intensity $I \gg 7.4 \times 10^{11} \text{ W/cm}^2$ for CO_2 laser in H_2 gas) Keldysh formula for the tunneling ionization rate $A(t)$ becomes

$$A(t) = 2.3 \times 10^7 (U_i^7/I)^{1/4} \exp[-2.5 \times 10^6 (U_i^3/I)^{1/2} (1 - 4.8 \times 10^9 U_i/I)], \quad (A9)$$

where A is in psec^{-1} , U_i in eV, and I in W/cm^2 .

To find the probability $B = \int A(t)dt$ behavior versus laser intensity with Gaussian laser pulse profile assumed according to Eq.(A5), Eq.(A9) was integrated over time interval $[-\Delta t/2, \Delta t/2]$ with $t=0$ corresponding to the peak of the laser pulse.[43]

The computed plots of $B(I_0)$ are presented in Fig.A1. Curve a corresponds to the pulse width $\tau_L = 50$ ps and the integration time $\Delta t = 50$ ps; curve b - $\tau_L = \Delta t = 10$ ps; and curve c - $\tau_L = \Delta t = 3$ ps. Note, that the attempted increase of the integration time to $\Delta t = 2\tau_L$ did not change results. The threshold laser intensity is slightly changing from $I_{th} = 0.7 \times 10^{14}$ W/cm² with $\tau_L = 50$ ps to $I_{th} = 1.0 \times 10^{14}$ W/cm² for $\tau_L = 3$ ps. This is an indication that just the peak field is really important in the tunneling process.

Comparing I_{th} values for avalanche and tunneling ionization, we may conclude which mechanism is prevailing under the specified gas medium and laser irradiation parameters.

Fig.A1

The tunneling ionization probability B vs laser peak power I_0 ; pulse width $\tau_L = 50$ ps and the integration time $\Delta t = 50$ ps; b) $\tau_L = \Delta t = 10$ ps; c) $\tau_L = \Delta t = 3$ ps.

Appendix B

ATF OPERATIONAL STATUS

In this Appendix, we give a description of the ATF relevant to the understanding of the technical feasibility of setting plasma waveguide experiments and plasma waveguide based laser acceleration experiments. Preliminary design parameters for such experiment are discussed in the main sections of this Study.

B.1 ATF Overview

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory is a users facility dedicated to research in the interaction of high-brightness electron beams with electromagnetic energy. For this mission, the ATF is equipped with a laser photocathode rf-gun, an electron linac, high power short pulse lasers synchronized with the electron beam and a variety of diagnostic equipment.

Fig.B1 presents the diagram of the ATF. The 12-ps bunches of electrons with 1 nC charge are produced by a laser photocathode electron gun with a 3 Hz repetition rate and are accelerated to 50 MeV by two RF travel-wave linac sections.

Laser system consists of Nd:YAG and CO₂ lasers. The 1.06 μm , 10-ps, 1 GW Nd:YAG laser serves for picosecond slicing in CO₂ laser system and, after frequency quadrupling, as a linac photocathode driver. The 10.6 μm , 50-ps, 10 GW CO₂ laser beam is transported to several locations in the experimental hall where it interacts with e-bunches to test different accelerator schemes.

Fig.B1
ATF Facility

B.2 Linac

Electrons originate from a photocathode of the rf-gun. Most robust copper photocathode with a quantum efficiency of 10^{-4} requires 50 μJ of the Nd:YAG 4th harmonic energy to produce photoelectrons of a 1 nC total charge. In the rf-gun

with a $1\frac{1}{2}$ cell cavity resonant to 2856 MHz rf-field driven from a klystron to as high as 12.5 MW power, photoelectrons are accelerated to 5 MeV by a 100 MV/m cathode field. Produced electrons are of ~ 4 mm-mrad normalized emittance and with a small energy spread of 17 keV due to the short laser pulse duration.

The ATF linac consists of two 3 m long, traveling wave linac sections driven by a 25 MW 2856 MHz klystron with a pulse duration 3.5 μ s at up to 6 Hz (regularly 3 Hz) repetition rate. Presently operated at 50-70 MeV energy, linac permits upgrade to 100-140 MeV if a klystron for each accelerating section is provided.

The electron beam diagnostics incorporates strip-line monitors for non destructive measurements of energy, current and beam position, remotely controlled destructive beam profile monitors based on phosphor screens and CCD cameras, and Faraday caps for beam charge measurements.

Two collimators with variable aperture incorporated in the post-linac beam transport line define small emittance beams for the laser acceleration experiments.

Three high-energy beamlines, installed in the experimental hall, permit convenient switch of the electron beam between several experiments that may be served nearly in parallel.

B.3 Nd:YAG Laser

The diagram in Fig.B2 shows main subcomponents of laser system and illustrates joined operation of YAG and CO₂ lasers serving for laser acceleration experiment. Actively mode-locked CW YAG oscillator generates a train of 12-ns spaced pulses of linearly polarized radiation, synchronized with the linac RF field. Pockels cell switch in combination with a polarizer cuts out single 15-ps pulses in a 3 Hz sequence. After 4-pass preamplifier and double-pass amplifier, pulses acquire 20 mJ energy. Part of this energy is split to control a picosecond slicing in CO₂ system. Other portion is directed through the second and then 4-th harmonic crystal to a photocathode generating 12-ps electron bunches.

Table B1 presents operational characteristics of the Nd:YAG laser. Application of a mode-locked laser as a RF gun driver puts exceptionally high requirements to the stability of all laser parameters. Bigger instabilities than whose specified in Table B1 would result in unacceptably high variations of accelerated electrons energy, beam emittance, aberrations, etc. Such stringent requirements to the stability are satisfied by using a diode pumped oscillator Lightwave 131 that is characterized by the appropriately small jitters in power and in mode-lock timing. Also, we use relay imaging and spatial filtering throughout the system, with long portions of beam path enclosed in evacuated tubes. Properly stabilized UV laser pulses are sent to a photocathode electron gun of the RF linac.

Fig.B2 ATF laser system

Table B1 Operational Characteristics of Nd:YAG Laser

Single pulse mode	
Total IR Energy	30 mJ
IR Energy Split to CO ₂ Laser	20 mJ
UV energy	0.3 mJ
Pulse Duration FWHM	
Oscillator	15 ps
Amplifier	25 ps
UV pulse	12 ps
Spot Size on Cathode [$1/e^2$ Ø]	0.1-1 mm
Shot-to Shot Stability on Cathode	
Pulse Timing Jitter	<1 ps
Pulse Duration Jitter	<1 ps
Energy	3%
Pointing [% of beam diameter]	3%
Pulse Train Mode	
Number of Pulses	200
Pulse Spacing	12 ns
Energy per Micropulse (IR)	1 mJ
Micropulse Energy Stability	2%

B.4 CO₂ Laser

B.4.1 Present Status

CO₂ laser, block-diagram of which is presented in Fig.B2, delivers high-power pulses of the IR radiation synchronized with the electron bunches. Such synchronization is automatically achieved by optical switching of several picosecond pulse out of 100-ns 1-MW oscillator output using the same YAG pulse which is ultimately used to drive a photocathode. After 8 passes through 1.2 m long 3-atm UV-preionized discharge, a CO₂ laser pulse is amplified to a 20 GW peak power.

The hybrid single-longitudinal zero-transverse mode grating tuned TEA CO₂ oscillator is the source of the 10- μ m beam. Single mode operation is provided by a combination of a low-pressure auxiliary discharge, with a gain spectrum as narrow as the longitudinal mode separation, and piezo-electric fine tuning of the cavity length. The oscillator produces 100-ns 1-MW laser pulse, with a smooth envelope without mode-beating.

Semiconductor switching method is used to cut out a several picosecond pulse from the oscillator output. Nd:YAG laser pulse having photon energy above the band gap of a semiconductor (Ge) creates an electron-hole plasma in a surface layer. When the plasma reaches critical density; refractive index becomes imaginary, and Ge, that is normally transparent to 10- μ m radiation, immediately turns into a high reflector. After the control pulse termination, the drop of the reflection from the Ge has a characteristic time of a diffusion of the free-carriers into the bulk material, 150 ps. To define the trailing edge of the pulse, shortening it to a few picoseconds, transmission switching, the complement to reflection switching, is used for the second stage. Using the same initiator for the linac and CO₂ laser, ensures the desired picosecond synchronization of the electron bunch and laser pulse at their interaction point.

In principle, the CO₂ pulse may be sliced as short as the electron bunch; that is ~ 12 ps. However, low level for the pulse duration is presently set by the amplifier bandwidth that depends upon the gas pressure. Presently, we use 3-atm UV-preionized amplifier. Fourier transform of its pressure-broadened rotational spectrum gives 50 ps. That is the shortest pulse that may be efficiently amplified without appreciable distortions.

To reach a power level needed for laser accelerator studies, the switched picosecond pulse must be amplified 10^4 - 10^5 times. A 3-atm multipass CO₂ amplifier pumped by a UV-preionized transverse electrical discharge serves for that purpose. The four passes through the 120-cm long amplifier discharge, energized by a 150-kV pulse, are arranged in a double-X configuration using a 4-mirror set-up. However, this brings the output only part ways towards the desired power level. To increase the total gain, we must address the problem of preventing parasitic self-lasing, caused by the extremely high gain conditions. This problem is solved by placing an optical isolator in the way of the amplified beam before redirecting it for the next 4 passes through the amplifier. The optical isolator consists of a polarizer with a Pockels cell in front of it. The polarizer is set in a crossed orientation to the ZnSe Brewster windows of the amplifier thereby blocking any radiation not strongly rejected by the amplifier windows. By

applying a short high-voltage pulse to the electro-optically birefringent CdTe crystal of the Pockels cell synchronously with the picosecond laser pulse arrival, we turn the optical polarization by 90° and transmit the pulse through the polarizer.

Assisting the electro-optical isolator with parasitic lasing suppression is an optical self-breakdown, initiated in the air by the four-pass amplified laser pulse. The dense plasma of the laser spark, created at the focal point of a telescope positioned before the Pockels cell, blocks the passage of parasitic radiation recycling through the amplifier. The plasma breakdown also shortens the width of the amplified pulse.

Ultimately, after 4 additional passes through the same amplifier, which are arranged in a similar way as the first 4 passes, we measure an output laser energy of 1 J. A single-shot autocorrelator indicates that the laser pulse width is 50 ps, which corresponds to the spectral-bandwidth-limited minimum pulse duration sustainable by the 3-atm CO₂ amplifier. Amplified to 20 GW peak power, 50-ps pulses are transported to the experimental hall, where they are used for electron acceleration experiments.

B.4.2 Terawatt CO₂ Laser Project

Most of the ATF experiments under way or planned will greatly benefit from further laser power increase over the existing 20-GW CO₂ laser. 100 GW or higher CO₂ peak laser power is needed to reach the DOE goals for laser accelerator studies of a 100 MeV demonstration and eventually, a 1 GeV accelerator. Based upon the capabilities of present laser technology and the modeling results of picosecond pulse amplification already verified experimentally at the ATF, it has been shown that a relatively compact single-beam picosecond CO₂ system, with two amplifier stages, is potentially scalable to the terawatt peak power level.[25] In this paragraph we explain our approach to building such a laser.

When estimating the energetic capabilities of CO₂ amplifiers, the following two intrinsic physical parameters play major roles: small signal gain $g_0 = \sigma_g N^*$, where σ is the gain cross-section and N^* is the population of the upper laser level; and saturation fluence $E_s = h\nu/2\sigma_g$. Parameters g_0 and E_s regulate the energy amplification process described by the Franz-Nodvik equation

$$E_{out} = E_s \ln\{1 + \exp(g_0 l) [\exp(E_{in}/E_s) - 1]\}. \quad (B1)$$

The product of these parameters divided by the pulse duration, τ_L , gives an estimate of the potential extractable peak power from the amplifier in a single pass in a saturated regime:

$$I = g_0 E_s l S / \tau_L, \quad (B2)$$

where l and S are the length and aperture of the amplifier, respectively.

According to Eq.(B2), laser pulse shortening should provide a nearly proportional increase of the laser peak power. However, shortening of the input laser pulse to the amplifier is limited by spectral matching requirements. The

nonuniform spectral gain in a molecular medium with a periodic modulated rotational spectrum modifies the spectral envelope, $S(\nu)$, of the pulse. The intensity envelope, $I(t)$, related to $S(\nu)$ by the inverse Fourier transform, will be correspondingly reshaped. The pulse may lengthen or even split into a train of pulses. The period in this train, δ , corresponds to the frequency interval between the centers of rotational lines, which is 18 ps for the 10P CO₂ band. Smoothing of the molecular spectrum via pressure broadening helps to minimize the laser pulse distortions.

An alternative way to achieve gain smoothing is to reduce the spectrum modulation period using an isotopic gas mixture. Replacement of one of the oxygen nuclei by that of a different isotope destroys the symmetry of the CO₂ molecule. This means that twice as many V-R transitions are allowed and the gain spectrum becomes twice as dense compared to a regular CO₂ molecule. If we consider a mixture of ¹²C¹⁶O₂, ¹²C¹⁶O¹⁸O, ¹²C¹⁸O₂ = 1:2:1, then, due to isotopic shifts, the combined spectrum will have within overlapped regions approximately 4-times denser rotational line structure than with a regular CO₂ molecule. Computer modeling shows that the reduction in the spectral line interval results in considerably less short-pulse distortion during amplification, and pulses as short as 3-ps may be amplified in a 5-atm multi-isotope amplifier.

The practical limit to intensity increase in picosecond CO₂ laser amplifier is ultimately set by the output window damage. The primary mechanism for optical damage in picosecond time scale will be avalanche breakdown. The avalanche mechanism assumes the invariance of the threshold fluence, E_{th} , with τ (for IR optics, $E_{th}=0.5$ J/cm²). Taking into account the optical window damage limitations and the limited extractable energy available from a unit active volume of the amplifier, a maximum possible beam diameter needs to be maintained during the final optical pass through the second amplifier stage.

Suggested arrangement for the modified ATF CO₂ laser system is illustrated in Fig.B3. Presently operational oscillator and picosecond pulse slicing system will supply a seed pulse into a regenerative preamplifier which may operate as a separate unit or may share a portion of the active discharge region of the final large-aperture amplifier. X-ray preionized multi-atmosphere CO₂ laser unit is chosen as an optimum device for the final amplifier. X-ray preionized discharge pumping, while somewhat more complex than UV-preionization, has many advantages in large-aperture high-pressure discharge applications. The higher photoelectron production, coupled with the long x-ray range, ensures that the entire discharge volume is filled with a high, uniform initial electron density required for stable discharge formation. The x-rays are produced in a separate chamber from the laser gas thus eliminating the hot gas regions associated with sparks which contribute significantly to the dissociation of CO₂, thus shortening gas lifetime. The high voltage required for the gun is ~100 kV, much smaller than the discharge voltage, and could possibly be tapped off the discharge pulser.

The discharge voltage and pump energy scale linearly with pressure. For instance, for a 10-atm (15% of the molecular content) gas mixture and an 8-cm interelectrode gap, the discharge voltage is 500 kV. Fig.B3(b) presents a schematic diagram showing one of possible concepts for the high-pressure, large-

aperture CO₂ amplifier, where in order to alleviate the stresses associated with the high voltages in this system, a bipolar LC-inversion generator is used. The bipolar technique applies a positive voltage +V to one electrode and a negative voltage -V to the other electrode resulting in a voltage difference between the electrodes of 2 V. The electrodes are housed in a insulating tube. The corona-plasma cathode x-ray source is mounted behind one of the electrodes, with a thinned out region in the center of the electrode to provide x-ray transmission into the discharge gap.

Fig.B3 Terawatt CO₂ laser project

Computer simulations of the picosecond CO₂ pulses amplification, based on a numerical solution of Maxwell-Bloch equations, were done for the laser system consisting of two amplification stages with a final three-pass amplifier of a 30 cm² output optical aperture. With a 5 GW input pulse, a 230 GW output peak power is predicted for a 30-ps pulse and 5 atm of amplifier pressure and 1 TW for 10-ps and 10-atm, correspondingly. Even higher peak power may be expected after shortening the seed pulse to a 3-ps bandwidth limit of a high-pressure CO₂ amplifier. Such short pulse may be generated using correspondingly short control pulse for slicing, or with a thin etalon. The theory and experiment on a transient response of the etalon tuned to the minimum reflection are described in

reference[49]. Results of the Maxwell-Bloch numerical simulation for a 3-ps laser pulse propagating in a 5-atm multi-isotope CO₂ amplifier are plotted in Fig.B4. Table B2 shows the results of modeling 5-passes through a 1-m long multi-isotope amplifier.

Fig. B4

Energy gain curve for 3-ps input pulse in 5-atm multi-isotope amplifier ($E(0)=2.3 \times 10^{-5} \text{ J/cm}^2$)

Table B2

5-passes of 3-ps pulse in 5-atm multi-isotope amplifier

($g_0 l = 1.35$, $E_s^* = 600 \text{ mJ/cm}^2$).

Pass	Diameter (cm)		$\mathcal{E}(\text{J})$		E (mJ/cm ²)		Amplification	Extraction (%)
	in	out	in	out	in	out	$\mathcal{E}_{\text{out}}/\mathcal{E}_{\text{in}}$	$\Delta E/E_s^* g_0 l$
1	2	2	0.03	0.10	10	33	3.3	3
2	2	2	0.10	0.33	33	110	3.3	10
3	3	3	0.25	0.82	35	115	3.3	10
4	3	7	0.82	2.7	115	70	3.3	15
5	7	7	2.7	9.0	70	230	3.3	20

B5 Present ATF Program of Laser Driven Electron Accelerator Study

The ATF schedule includes three laser acceleration experiments approved by the CAP Steering Committee. One of them, IFEL,[4] illustrated by Fig.B5, is based on accelerating action of linearly polarized laser beam onto electrons having oscillating trajectory inside a wiggler. Transverse laser field has an electrical component along the local direction of the e-beam propagation. Pondermotive force produces an additional kick to the electrons in the direction of propagation if the laser field is in phase with wiggling. Synchronism conditions may be satisfied by adjusting a wiggler field and period. To ensure uniform acceleration condition over the 0.5 m length of the wiggler, e-beam and CO2 laser radiation will be channelled in a sapphire waveguide. Table B3 presents design parameters for the IFEL experiment. The full scale experiment requires a 200 GW laser, and the projected acceleration gradient is 90 MeV/m.

Fig.B5 IFEL accelerator

Table B3

Design Parameters for IFEL Experiment

Wiggler	
Length	47 cm
Period	2.86-4.32 cm
Gap	0.4 cm
Field	1.25 T
Electron Oscillation	0.17-0.22 mm
CO ₂ Laser Driver	
Peak Power	200 GW
Waveguide Losses	0.025 m ⁻¹
Mean Accelerating Field	89 MV/m

Other scheme called Grating Accelerator,[6] illustrated by Fig.B6, is based on an excitation of evanescent surface field when a laser beam is cylindrically focused onto a periodical structure. Electrons injected along the surface will be accelerated when moving in phase with the standing wave oscillation. This process is similar to what is observed in the RF linac. That is why it is also called Grating Linac. Operating parameters for this experiment are presented in Table B4. For a relativistic e-beam, to satisfy synchronism conditions, structure period is nearly equal to the laser wavelength.

Fig.B6 Grating Linac

Table B4

Design Parameters for Grating Linac

CO2 Laser Power	1 GW
Intensity	0.3 TW/cm ²
Cylindrical Lens f-Number	5
Transverse Focus Size	50 μm
Interaction Length	3 mm
Electron Beam Radius	0.7 μm
Accelerating Field	1.5 GV/m

In third scheme shown in Fig.2, we start with a radial polarized beam. Using axicon, laser beam will be converged to the e-beam axis. Because of the wave-front inclination, a longitudinal component of the electric field will be developed. At phase-matching condition satisfied by filling hydrogen into the

interaction cell, the injected electron bunch propagates in phase with the optical field and experience an acceleration. This process is opposite to the coherent Cherenkov radiation. That is why the described laser-driven electron acceleration scheme is called Inverse Cherenkov Accelerator (ICA).[1,2]

Converged by the axicon, radially polarized laser beam produces cylindrically symmetrical interference pattern. A longitudinal component of the electric field has a maximum along the axis similar shown in Fig.6. The width of this maximum under the conditions of the ATF experiment is 400 μm , the same as the diameter of the e-beam.

In the first ICA run using 0.7 GW CO_2 laser beam, up to 3.5 MeV peak acceleration has been observed.[14] Up to 12 MeV acceleration over a 20 cm interaction distance is predicted by a computer simulations for a 5 GW laser driver power.[2] These figures are subject to experimental verification in the next ICA run.

Table B5

Design Parameters for ICA Experiment

Cherenkov Angle	20 mrad
Phase Matching Gas	H_2
Gas Pressure	1.7 atm
Interaction Length	20 cm
Electron Beam Diameter	0.4 mm
Net Acceleration (@ 0.6 GW)	3.7 MeV
Predicted Acceleration (@50 GW)	36 MeV
E_a at gas breakdown limit	~600 MeV/m

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