CO₂ Laser Technology for Advanced Particle Accelerators

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CO₂ LASER TECHNOLOGY
FOR ADVANCED PARTICLE ACCELERATORS

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Abstract

Short-pulse, high-power CO₂ lasers open new prospects for development of high-gradient laser-driven electron accelerators. The advantages of λ=10 μm CO₂ laser radiation over the more widely exploited solid state lasers with λ≈1 μm are based on a λ²-proportional ponderomotive potential, λ-proportional phase slippage distance, and λ-proportional scaling of the laser accelerator structures. We show how a picosecond terawatt CO₂ laser that is under construction at the Brookhaven Accelerator Test Facility may benefit the ATF’s experimental program of testing far-field, near-field, and plasma accelerator schemes.

I. INTRODUCTION

Lasers are the sources of the most intense electromagnetic radiation and strongest electric and magnetic fields available for laboratory research. For example, focusing of a terawatt laser beam into a 10-μm spot results in intensity of $10^{18}$ W/cm² and, associated with it, an electric field of 30 GV/cm that exceeds by five orders of magnitude fields attainable in conventional particle accelerators. Such capability stimulates a new high-energy physics discipline to emerge: laser-driven high-gradient particle accelerators. The primary practical goal is to find an alternative to conventional accelerators in order to build, in the future, more economical high-energy (~TeV) machines, or compact moderate-energy (~GeV) accelerators.

Presently, a variety of acceleration methods are under consideration and study. All laser accelerator schemes proposed so far may be split into three major categories: far electromagnetic (EM) field, near EM field, and plasma accelerators. How to define the border between the first two methods? EM field may be presented as a sum of propagating EM waves

$$\vec{E}(\vec{r},t) = \sum_j A_j \exp[i(\vec{k}_j \times \vec{r}_j - \omega_j t)].$$  (1)

When all wave vectors $\vec{k}_j$ are real, we talk about far field accelerators. For these schemes it is essential that any distances from the source of the field or from any boundary surface are $>>\lambda$. Otherwise, near field effects come into play.

Fields with imaginary $\vec{k}_k$ are called near fields. Actually, in this case, we talk about evanescent EM fields vanishing within a λ-thick layer above the surface.

In the third group of methods, particles are accelerated not by EM fields directly but by electrostatic fields due to the charge separation in laser-induced plasma waves. So far, the record of ~100 MeV over the 0.5 cm distance laser acceleration has been achieved using laser wakefield acceleration (LWFA) in plasma[1].

In general, particle acceleration by a fast-oscillating electromagnetic field becomes possible when a relativistic particle moves in synchronism with the phase of the driving field. The long wavelength of a CO₂ laser helps to meet this requirement. This feature is of particular importance for far-field acceleration schemes, examples of which are the Inverse Cherenkov Accelerator (ICA)[2,3] and Inverse Free Electron Laser (IFEL) accelerator[4,5].

Proposed near-field accelerator schemes, Grating Linac[6] and Resonant Accelerator[7], are based on the accelerating action of evanescent fields developed near the periodically shaped surfaces under laser irradiation. Since the
spatial scale of such structures is comparable with the laser wavelength, these schemes look practical when a CO₂ or longer-wavelength laser is used as the accelerator driver.

Among known plasma-based laser acceleration techniques, self-modulated LWFA[8] looks presently the most promising. This method requires a so-called "relativistically strong" laser beam that satisfies conditions for relativistic self-focusing in plasma. With the CO₂ laser, this condition may be satisfied at a 100 times lower plasma density than with a 1-μm laser of the same power. Another advantage of CO₂ lasers for plasma accelerators is based on a λ²-proportional ponderomotive potential that controls the intensity of the laser-induced plasma wake. Simulations demonstrate a possibility to accelerate electrons by 250 MeV over a 4 cm distance using properly shaped 5 TW CO₂ laser pulses propagating inside a low-density plasma channel[9].

The approach to utilize the long-wavelength laser radiation for particle acceleration study is pursued at the ATF where the first terawatt picosecond CO₂ laser is under construction to study electron acceleration using far-field, near-field, and plasma acceleration schemes. We discuss here how all these schemes can benefit from using the CO₂ laser.

Description of the ATF, its current experiment program, and design of the present and upgraded laser system can be found elsewhere[10,11]. Table 1 summarizes the performance characteristics of the ATF primary components: photocathode RF linac and CO₂ laser system.

| CO₂ Laser (Present) |  |
|---------------------|--|---|
| Pulse Duration [ps] | 100 | |
| Output Energy [J]   | 1  | |
| Output Peak Power [GW] | 10 | |
| Repetition Rate [Hz] | 0.1 | |

| CO₂ Laser (Upgrade) |  |
|---------------------|--|---|
| Pulse Duration [ps] | 3  | |
| Output Energy [J]   | ~15 | |
| Output Peak Power [TW] | ~5  | |
| Repetition Rate [Hz] | 0.1 | |

| LINAC |  |
|-------|--|---|
| Bunch Duration FWHM [ps] | 0.4-10 | |
| Electron Energy [MeV] | 50 | |
| Peak Current [A] | 170-50 | |
| Electron Energy Spread [%] | 0.2 | |
| Normalized Emittance [mm.mrad] | 0.5-2 | |
| Repetition Rate [Hz] | 3 | |

II. FAR FIELD ACCELERATORS

II.1. Inverse Cherenkov Accelerator

In any laser acceleration scheme, the key question is how to maintain synchronism between particles and oscillating electric fields over an appreciable distance. One of the possibilities is when the particle, traveling in medium with velocity βc, is intersected by the EM wavevector at the Cherenkov angle, θ, which is described by the condition

$$\cos \theta = \beta n^{-1}.$$  \hspace{1cm} (2)

Here, the inclination of the wavevector is responsible for developing a longitudinal accelerating field component, while the medium is chosen to produce retardation of the phase velocity of the wave to match the speed of electrons. Inverse
Cherenkov acceleration is the only example of a first order, far field acceleration process where the particle interacts with a single EM wave.

In the first ICA demonstration at Stanford University[12], a linear polarized, focused Nd laser beam crossed the path of electron beam in the interaction cell filled with hydrogen. The observed energy shift was 50 keV over the 7 cm interaction length.

In a modified scheme[2] (see Fig.1) which is under test at the ATF, we start with a radially polarized beam. By an axicon, the laser beam is converged to the e-beam axis, z, producing a cylindrically symmetrical interference pattern. An amplitude of the longitudinal component of the electric field, which is responsible for electron acceleration, is described analytically by Bessel function of the first kind of the order 0:

\[ E_z(r, z) = ig \theta \times E_0(z)J_0(2 \pi \theta r / \lambda), \]

where \( E_0(z) \) is a field amplitude that depends upon the laser intensity distribution at the axicon surface, \( W(R) \),

\[ E_0(z) = 2 \pi \theta \sqrt{2z W(R)} \]

with \( z = R/\theta \). The distribution described by Eq.(3) has the maximum along the z axis that defines the acceleration gradient attainable under the phase matching condition, Eq.(2). The radial position of the first minimum in the distribution Eq.(3) is observed at

\[ r_{min} = 0.38 \lambda / \theta ; \]

for \( \lambda = 10.6 \) μm and \( \theta = 20 \) mrad, \( r_{min} \approx 200 \) μm. In a practice, the parameter \( r_{min} \) shall be chosen according to the realistic size of the e-beam, \( r_{min} \approx r_e \), that propagates along the axicon axis. Then, as follows from Eq.(5), the longer \( \lambda \) permits to choose the proportionally bigger angle \( \theta \). Combining this condition with Eqs.(3) and (4), we come to the conclusion: \( E_x \sim \lambda \beta^2 \), due to stronger inclination of the laser wavefront to the e-beam propagation.

Fig.1  Axicon focusing of radially polarized laser beam in the inverse Cherenkov accelerator

Another advantage of using the relatively long-wavelength CO2 laser radiation for the ICA scheme is due to the increase of the "phase slippage" distance, \( L_{slip} \), where the accelerating particle stays in partial synchronism with the driving EM field. The expression for \( L_{slip} \) comes from the condition \( L_{slip} \Delta \beta = \lambda / 2 \), where \( \Delta \beta \) is the electron velocity increase above the \( \beta \)-number defined by Eq.(2). Using \( \beta = \sqrt{1 - 1/\gamma^2} \), we derive

\[ L_{slip} = \frac{\lambda \gamma^3}{2 \Delta \gamma}. \]

For example, for the conditions of the ATF ICA experiment, \( L_{slip} = 20 \) cm at \( \Delta \gamma = 25 \) that corresponds to the 12.5 MeV electron acceleration. It becomes evident that the 1-μm laser would require much stronger acceleration gradient in order to attain similar net acceleration over the 10 times reduced distance. However, that requirement would be difficult to satisfy considering the above mentioned proportion \( E_x \sim \lambda \beta^2 \).

So far, maximum 3.7 MeV acceleration has been measured when \(~1 \) GW CO2 laser power was delivered to the interaction region. After the completion of the ongoing ATF CO2 laser upgrade to a 3 ps pulse duration, up to 200 GW laser peak power may be delivered into the hydrogen cell prior to gas breakdown or optics damage. Monte-Carlo computer simulation of the ICA process shows a possibility of a 100 MeV acceleration demonstration over the 30 cm long interaction range.[13,14] To avoid phase slippage, gradual or step-wise change of the Cherenkov angle will be introduced over the
interaction distance. To produce monochromatic accelerated electrons, the short electron bunches should be phased with the peak accelerating field. For this purpose, periodical electron prebunching with the spatial interval equal to the laser wavelength will be produced in the IFEL accelerator section placed upstream the high-power ICA accelerator cell.

II.2 Inverse FEL Accelerator

The IFEL scheme is an example of a second order, far field laser acceleration process. In this case, a second field of a wiggler magnet is used to bring the relativistic particles into a transverse oscillating motion. Thus, transverse EM laser field has a projection of its electrical component along the local direction of the e-beam propagation (see Fig.2). Hence, electric forces may produce an additional kick to the electrons in the direction of their propagation, provided the laser field is in phase with the electron wiggling.

\[ \lambda = \frac{\lambda_w}{2\gamma^2} (1 + K^2) \]

where \( K \) is a dimensionless wiggler parameter equal to \( K = \frac{e B_w \lambda_w}{2 \pi n c^2} \) and \( B_w \) - wiggler magnetic field. Hence, the condition Eq.(7) may be satisfied over a long acceleration distance by adjusting wiggler field and period.

First proposed in 1972 [4], IFEL acceleration has been demonstrated using FEL[15] and a moderate-power CO\textsubscript{2} laser[16] as drivers.

The goal of the ATF IFEL experiment is further optimization of the accelerator parameters at a higher CO\textsubscript{2} laser power. The laser beam is guided inside a low-loss sapphire waveguide of a 2.8 mm internal diameter mounted inside the 0.5 m-long wiggler.

Electron spectra obtained during the ATF IFEL experiment show that practically all the electrons are trapped and accelerated. Because of problems with vacuum degradation when the laser is delivered inside the guide, the laser power has been kept below 0.5 GW. Observed acceleration is 2.2%. Further optimization is under way.

Near term plans call for increasing the CO\textsubscript{2} laser power to 200 GW. This should result in the accelerating gradient of \( \sim 100 \text{ MeV/m} \).[5]

IFEL is also expected to be a good buncher. In the mentioned above oncoming ATF experiment, electrons bunched in the IFEL to the period of \( \lambda \) will be sent to the ICA interaction cell to demonstrate quasi-monochromatic acceleration. A challenge in this experiment is to produce, deliver through the e-beam transport and focusing system, and maintain during the ICA process tiny electron bunches sized to the fraction of \( \lambda \). To achieve this goal with the long-wavelength CO\textsubscript{2} laser is a problem. But with the \( \lambda \approx 1 \mu\text{m} \), the same may be hardly feasible.
III. NEAR FIELD ACCELERATORS

III.1 Grating Linac

Near-field laser accelerator scheme illustrated by Fig.3 is based on excitation of an evanescent field when a laser beam is cylindrically focused onto a periodic structure, e.g., diffraction grating. Electrons injected parallel to the surface will be accelerated when moving in phase with standing wave oscillations. This approach is similar to the RF linac, and is therefore known as a Grating Linac[6]. For a relativistic e-beam to satisfy the synchronism conditions, the structure period is nearly equal to the laser wavelength. Thus, a long-wavelength CO₂ laser radiation helps to use reasonably "macroscopic" structures that may be produced by a conventional lithographic etching technique. Taking into account that the evanescent accelerating field is observed within one-wavelength distance from the surface, the requirement to the electron beam dimensions are also not as severe as would be with the 1-μm laser driver. In addition, the reduced phase slippage at a long wavelength is relevant for this scheme as well.

Fig.3 Principle diagram of the grating linac

When a 1 GW CO₂ laser beam is focused to the 5×0.03 mm strip at the "foxhole" structure, 1 GeV/m acceleration is predicted[17]. Using a short, picosecond laser pulse is a way to avoid the optical damage of the structure. To ensure the interaction of the e-bunch, directed perpendicular to the laser beam, over the appreciable acceleration distance (much longer than the laser pulse length), a linear delay shall be introduced across the laser intensity front. It may be done by reflecting the laser beam from the diffraction grating prior to cylindrical lensing.

III.2 Dielectric-Loaded Resonant Laser Accelerator

In another proposed near-field electron accelerator scheme[7], linearly polarized laser radiation penetrates through the periodically modulated dielectric structure filling the gap of the Fabry-Perot interferometer as shown in Fig.4. At the high quality factor of the interferometer cavity, Q, equal to the number of the optical double passes required to reach the field saturation in the cavity, a large stored EM energy and field amplitude can be obtained at the relatively low input laser power. Periodic modulation of the permittivity, ε, within the dielectric masks sandwiched between the interferometer mirrors

\[ \varepsilon(z) = \varepsilon_0 + \Delta \varepsilon \cos(2\pi \ell / \lambda) \]  

ensures a space-periodical modulation of the field phase in the central vacuum gap, provided the gap width is of the order of the laser wavelength. The electron beam, propagating inside the vacuum gap in the direction of the laser beam polarization, experiences acceleration due to the synchronously oscillating electric field. The average accelerating field is
where \( I \) is the incident laser intensity. The accelerating field in excess of 1 GV/m has been estimated for the realistic experimental parameters.

Similar to Grating Linac, this scheme looks more practical with the relatively long-wavelength CO\(_2\) laser, provided the problem of laser damage of the structure is solved.

**IV. LASER-DRIVEN PLASMA ACCELERATORS**

It looks logical to use a high-power CO\(_2\) laser, which is a strong ionizer, in the schemes where such ionization and related effects are not problems but are desirable, as it happens in plasma accelerators.

An EM wave packet propagating in plasma ponderomotively separates charges initiating their oscillation at the plasma frequency, \( \omega_p \), that depends upon the electron density, \( N_e \), by

\[
\omega_p = 2e(\pi N_e / m)^{1/2}.
\]  

(10)

Plasma wave follows the laser pulse with a phase velocity equal to the group velocity of the laser pulse,

\[
v_{ph} = v_{gr} = cn,
\]

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

A relativistic particle propagating together with plasma wave will experience acceleration until it slips out of synchronism over the distance

\[
l_a = \lambda_p (\omega / \omega_p)^2.
\]  

(11)

Initiated via oscillation of free plasma electrons in the laser field, amplitude of a plasma wave is proportional to the energy of the electron oscillatory motion called ponderomotive potential

\[
W_{osc} = e^2 E_L^2 / 2 m a^2,
\]  

(12)

where \( E_L \) is the laser field amplitude. This quadratic dependence of the ponderomotive potential upon the laser wavelength makes CO\(_2\) laser an attractive candidate to drive plasma accelerator.

Amplitude of the accelerating field due to the longitudinal charge separation depends upon the particular method of the plasma wave excitation.

In the LWFA scheme, plasma waves are initiated by an instant "shock" that is produced with a short laser pulse optimally equal in duration to the half-period of the plasma wave, \( \tau_L = \lambda_p / 2c \). Note, that after developing a high-power picosecond CO\(_2\) laser, there will be the first-time opportunity to use CO\(_2\) laser in this scheme in a practically meaningful range of the plasma density, \( N_e = 10^{14} - 10^{15} \) cm\(^{-3}\). The advantage of using CO\(_2\) laser in the LWFA scheme stems from the proportionality of the accelerating field to the laser wavelength that is the result of the strong ponderomotive potential in the CO\(_2\) laser field and, in particular, follows from the expression[8]
\[ E_a = \frac{\pi^2 mc^2 a^2}{4\lambda_p e^{1+2a^2/2}}, \]  
\[ a = eE_L / m \]  
where \( a \) is the unitless laser strength parameter.

In the laser beatwave accelerator (LBWA) scheme we choose periodical force that matches the plasma frequency and resonantly enhances plasma oscillations. Such laser intensity modulation is produced by mixing two laser beams of different frequencies that satisfy a condition \( \omega_1 - \omega_2 = \omega_p \).

The accelerating field in the LBWA reaches an amplitude of
\[ E_a = (5a_1a_2)^{1/3} N_e^{1/2}. \]  
Thus, due to the proportion of \( E_a \propto \lambda^{2/3} \) (see Eqs.(14) and (15)), CO₂ laser can produce 6 times stronger acceleration than a 1-μm laser of the equal intensity.

Exploiting this feature, up to 30 MeV acceleration over a 1 cm interaction distance has been demonstrated using subnanosecond, multi-gigawatt, dual-wavelength CO₂ lasers.\[18,19\] The expected enhancement of the acceleration gradient with a picosecond terawatt CO₂ laser is due to higher stability of the fast-excited wakefield.

The third, self-modulated (SM) LWFA scheme, looks the most promising. It comes to the scene when the laser pulse is relativistically strong. Relativistically strong means that laser power, \( P \), satisfies the condition of relativistic self-focusing
\[ P \geq 17(\omega/\omega_p)^2 \left[ GW \right]. \]  
In this case, initially small plasma density oscillations cause modulation at the plasma frequency of the laser beam envelope and its intensity. Then, the pulse resonantly enhances the plasma oscillation similar to the LBWA scheme matched automatically to the local plasma density. It is understood that the laser pulse length in this case shall extend over several plasma periods, \( \tau_L \geq 2\pi/\omega_p \).

It has been shown by simulations that, if the laser pulse is just strong and long, it is still not enough to produce an intense and regular wave[9]. The wake needs an efficient initiation, similar to that provided in the LBWA or LWFA schemes. One of the possibilities is when a steep leading front, with \( \tau_{le} < \lambda_p/c \), serves as a good initiator for a plasma wave. Simulations done for a 5-TW, 1.5-ps, appropriately shaped CO₂ laser pulse propagating in a plasma channel[9] predict electron acceleration to 250 MeV.

Finally, let us address the question of how to compare potential performance of 10-μm and 1-μm lasers in the SMLWFA configuration. An accelerating field attainable at the plasma wave breaking limit is
\[ E_a \propto \omega a^2 / \sqrt{1+a^2 / 2}. \]  
According to Eq.(14), \( a \) is proportional to \( \lambda \). In spite of this fact, the expression for the net acceleration
\[ \gamma_{max} \propto \omega a^{2/3}, \]  
obtained from Eqs.(11) and (17), still seems beneficial for shorter wavelength lasers. However this first impression is misleading. The thing is that, for the SMLWFA scheme, the choice for parameters entering Eq.(18) is not arbitrary. The values of \( \omega \) and \( \omega_p \) are linked together through the self-focusing condition, Eq.(16).

Assume for our wavelength comparison two laser beams of the equal power but different wavelength, both close to the relativistic self-focusing condition, and focused to the equal spot size. Then, the ratio \( \omega/\omega_p \) should be chosen equal for any laser wavelength. The result of it is that the maximum acceleration is proportional to \( \lambda, \gamma_{max} \propto \lambda \sqrt{P} \).

When \( \lambda=1 \) μm, we need to channel the laser beam and, hence, e-beam in a 10-μm waveguide in order to obtain similar acceleration as with the CO₂ laser beam inside a 100-μm waveguide. Doing it, we may encounter severe problems with the electron beam scattering. Indeed, when we increase \( \omega \) and \( \omega_p \) 10 times, the plasma density will be increased 100 times, according to Eq.(10), with the increase of the multiple scattering in the gas according to the formula[20].
\[ \Delta \theta_{1e} = (W_s / W)(z / L_R)^{1/2}[1 + 0.1 \log_{10} (z / L_R)], \]  
where \( \Delta \theta_{1e} \) is the angular spread of the e-beam, \( W \) is the mean electron energy, \( W_s=19.7 \) MeV is a multiple scattering constant, \( z \) is the path length through the gas traversed by the electron, and \( L_R \) is the radiation length of the medium, which

\[ E_a = \frac{\pi^2 mc^2 a^2}{4\lambda_p e^{1+2a^2/2}}, \]
\[ a = eE_L / m \]
is the unitless laser strength parameter.
for hydrogen gas is \( L_p = 7 \times 10^5 \text{ [cm]/[atm]} \). The result of gas scattering is the e-beam emittance growth and reduced acceleration efficiency due to a poor overlap of the diverging e-beam with the narrow channeled laser beam. A simplified formula for the e-beam radius growth due to the multiple scattering

\[
\Delta r(z) = \frac{2}{3} \frac{W_s}{W} \sqrt{L_R} z^{3/2}
\]

indicates that the e-beam expands by \( \Delta r = 10 \mu\text{m} \) over the distance of \( z = 2 \text{ cm} \) in a 0.25 atm of H\(_2\).

It follows that the CO\(_2\) laser, that permits similar acceleration at 10 times wider waveguide and e-beam diameters and a 100 times lower pressure, looks more attractive for a prospective high-energy plasma accelerator.

Considering the feasibility of conducting a sub-GeV plasma acceleration experiment at the ATF, we should remember that not just a terawatt CO\(_2\) laser will be available for this purpose, but also one of the world's brightest e-beams that may be fitted inside a 100-\(\mu\text{m} \) wide channel. Fig. 5 shows the principal schematic of the ATF LWFA experiment where a plasma channel is produced via gas ionization by axicon-focused linear or radial polarized laser beam [21]. A split fraction of the drive CO\(_2\) laser beam may be used for this purpose. Parameters of the hypotetic LWFA experiment are presented in Table 2.

Dielectric capillary tubes may offer another possibility for guiding high-power laser beams in LWFA. This opportunity is based on a finite velocity of the plasma front that is originated at a capillary wall due to the laser ablation. At a typical plasma implosion velocity of several km/sec, it should take several nanoseconds for the overdense plasma to fill a capillary. Thus, the picosecond laser pulse will not be effected by the capillary ablation. Test with a picosecond Nd:YAG laser [22] shows the viability of this approach.

![Fig. 5 Principal diagram of the LWFA experiment](image)

**V. CONCLUSIONS**

The first terawatt picosecond CO\(_2\) laser is under construction at the ATF. There are several reasons why we are interested in using a CO\(_2\) laser for particle acceleration:

- With far-field accelerators, we may benefit from a slow phase slippage.
- For near-field accelerators, the CO\(_2\) laser helps to use macroscopically-sized accelerator structures and e-beams.
- With plasma accelerators, we capitalize on the strong ponderomotive potential of electron, oscillating in the laser field, and all outcomes of it such as: strong plasma wave formation, relativistic self-focusing at a low plasma density, etc.

We intend to utilize all above-listed features of the picosecond terawatt CO\(_2\) laser to benefit the laser acceleration experiments at the ATF. So far, high-brightness, 10-ps, 50-MeV electron bunches have been accelerated to several MeV at the ATF with the \( \sim 1 \) GW CO\(_2\) laser pulse using far-field accelerator schemes. Due to the expected acceleration scaling as a square root of the laser power, 100 MeV ICA and IFEL demonstration is possible after the laser upgrade. Combined IFEL-ICA experiment is under preparation to enhance the acceleration efficiency by the electron periodical prebunching at the laser wavelength.

Laser linac near-field accelerator experiment is scheduled for tests.
By the SMLWFA method, 250 MeV acceleration over a 4-cm distance is feasible when using the properly shaped 5-TW laser pulse guided in a plasma channel.

Table 2. Design Parameters of the LWFA Experiment with CO₂ Laser Driver

<table>
<thead>
<tr>
<th>Seed Electron Beam</th>
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<tbody>
<tr>
<td>Electron Energy [MeV]</td>
<td>50-70</td>
</tr>
<tr>
<td>Bunch Duration FWHM [ps]</td>
<td>0.4-10</td>
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<td>Electron Energy Spread [%]</td>
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<tr>
<td>Normalized Emittance [mm.mrad]</td>
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<td>Peak Current [A]</td>
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<table>
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<tr>
<th>Plasma Channel by Axicon-Focused CO₂ Laser</th>
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<tbody>
<tr>
<td>Laser Energy [J]</td>
</tr>
<tr>
<td>Channel Radius [μm]</td>
</tr>
<tr>
<td>Axicon Angle [mrad]</td>
</tr>
<tr>
<td>Channel Length [cm]</td>
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<tr>
<td>Plasma Density Inside the Channel [cm⁻³]</td>
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<tr>
<td>Plasma Density at r = rₖ [cm⁻³]</td>
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<table>
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<th>Laser Accelerator</th>
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<tr>
<td>Laser Peak Power [TW]</td>
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<tr>
<td>Laser Pulse Duration [ps]</td>
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<tr>
<td>Laser Radius at Focus [μm]</td>
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<tr>
<td>Laser Peak Intensity [TW/cm²]</td>
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<td>Acceleration Gradient [GV/m]</td>
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<td>Pump Depletion Length [cm]</td>
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<td>Rayleigh Length [cm]</td>
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<tr>
<td>Interaction Length [cm]</td>
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<td>Energy Gain with Guiding [MeV]</td>
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