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Emerging Terawatt Picosecond CO_2 Laser Technology

I.V. Pogorelsky

Accelerator Test Facility, National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.A

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National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973

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I.V. Pogorelsky

Accelerator Test Facility, Brookhaven National Laboratory, 725C, Upton, NY 11973, USA

ABSTRACT

The first terawatt picosecond (TWps) CO_2 laser is under construction at the BNL Accelerator Test Facility (ATF). TWps-CO_2 lasers, having an order of magnitude longer wavelength than the well-known table-top terawatt solid state lasers, offer new opportunities for strong-field physics research. For laser wakefield accelerators (LWFA) the advantage of the new class of lasers is due to a gain of two orders of magnitude in the ponderomotive potential. The large average power of CO_2 lasers is important for the generation of hard radiation through Compton back-scattering of the laser off energetic electron beams. We discuss applications of TWps-CO_2 lasers for LWFA modules of a tentative electron-positron collider, for γ-γ (or γ-lepton) colliders, for a possible "table-top" source of high-intensity x-rays and gamma rays, and the generation of polarized positron beams.

1. NEW CLASS OF TERAWATT PICOSECOND LASERS

Table-top terawatt (T^3) picosecond and subpicosecond solid state lasers are the sources of the most intense electromagnetic radiation and strongest electric and magnetic fields available for laboratory research. However, progress in the newly emerged strong-field physics applications, such as laser accelerators or laser synchrotron x-ray sources, to high repetition rate devices is impeded by the low average power of the T^3 lasers. This is due to the inherently low efficiency of the thermal diffusion cooling of the solid active elements. Much more efficient convection heat exchange may be implemented in the fast-flow gas lasers. The demonstrated high output energy and power of molecular and eximer lasers make them a rational complement to solid state laser technology. CO_2 lasers operating in the mid-IR spectral region (λ=10 μm) deserve the most attention. This is not just because the absolute maximum average power has been demonstrated with these devices, but also due to favorable wavelength scaling of a number of light-matter interactions.

The relatively long nanosecond pulse duration of conventional CO_2 lasers is the prime reason why the potentials of CO_2 lasers have not been utilized so far in a full manner for high-energy physics research. Kilojoules of laser energy would be required to reach a terawatt peak power. This is still possible with CO_2 lasers, as it has been demonstrated previously. However, such lasers are very bulky and are not capable of high repetition rates. There is also a problem to deliver such a high laser energy to the interaction point without optics damage. And finally, the nanosecond pulses are incompatible with many of the strong-field physics processes which are typically localized in very short time and space intervals. Thus a picosecond and shorter pulse duration turns out to be a prerequisite for the successful use of lasers in advanced scientific applications.

A physical parameter that enables generation and amplification of picosecond laser pulses is the gain spectral bandwidth. In solid state lasers, radiation transitions in outer electron shells of active ions are broadened to 5-50 THz due to the perturbation action by the host matrix. Such a broad gain spectrum makes possible the generation of picosecond, and even femtosecond, laser pulses by the mode locking technique. Unlike a solid state, the spectral gain in the molecular gas discharge is periodically modulated by the rotational structure. Due to the discrete spectrum, and for other physical and technical reasons, mode-locking techniques do not work for CO_2 lasers as well as for solid state lasers. However, alternative methods to produce picosecond and sub-picosecond CO_2 laser pulses have been developed. One of them is semiconductor optical switching. Using this method, subpicosecond CO_2 laser light slices has been demonstrated [1].

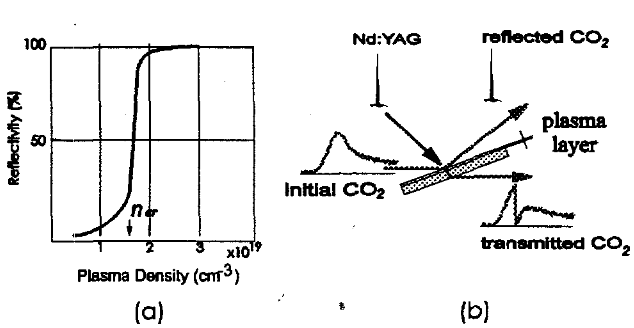

FIGURE 1. Principles of semiconductor optical switching:
a) reflectivity of Brewster Ge window versus surface free-electron density; b) transition reflection from semiconductor optical switch.

Illustrated in Fig.1 by the example of the ATF laser system [2], the optical switching process works as follows. Nd:YAG pulse having photon energy above the band gap of germanium creates an electron-hole plasma in a surface layer. When the plasma reaches the critical density the refractive index becomes imaginary, and Ge, which is normally transparent to the 10-μm radiation, immediately turns to a metal-like mirror. After the control pulse termination, the drop of reflection from the Ge has a characteristic time of diffusion of the free-carriers into the bulk material which is ~150 ps. To define the trailing edge of the pulse thereby shortening it to a few picoseconds, the complement to reflection switching, transmission switching, is used for a second stage.

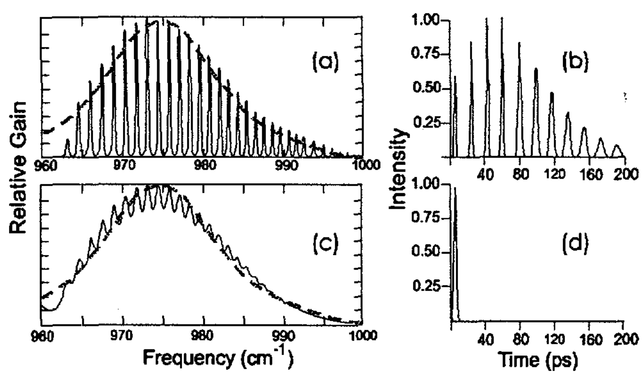

FIGURE 2. Picosecond CO_2 laser pulse amplification:
a) CO_2 gain spectrum at 1 atm (dashed line shows spectral envelope of 1 ps CO_2 pulse); b) 1 ps pulse splits into train after propagation through 1 atm laser amplifier (simulation); c) CO_2 gain spectrum at 10 atm matches 1 ps pulse; d) 1 ps pulse is amplified in 10 atm laser amplifier without distortions.

We know how to produce a short pulse. Now we need to amplify it. When a picosecond laser pulse propagates in a gas with a periodic modulated rotational spectrum, the nonuniform spectral gain modifies its spectral envelope; see Fig.2(a,b). The intensity envelope, related to the spectrum by the inverse Fourier transform, will be correspondingly reshaped. The pulse will split into a train of pulses. The period in this train, 18 ps, corresponds to the frequency interval between the centers of rotational lines. Smoothing of the molecular spectrum via pressure broadening helps to minimize the laser pulse distortions; see Fig.2(c,d).

An alternative way to achieve gain smoothing is to reduce the spectrum modulation period using an isotopic gas mixture $CO_2^{16}:CO^{16}O^{18}:CO_2^{18}$. Due to isotopic shifts, the combined spectrum has four times denser rotational line structure than with a regular CO_2 molecule. The theoretical limit to the pulse duration, defined by the total 1 THz bandwidth of the CO_2 vibrational band, is 0.5 ps. The 0.8 ps pulses have been demonstrated [3]. At that time they were produced in a several cubic centimeter discharge volume at a millijoule level, thus the peak power was still at a gigawatt level.

To attain a terawatt peak power, a ~10-atm, ~10-l CO_2 amplifier is required. To maintain a uniform discharge under such conditions, the following requirements should be satisfied: a) strong penetrating preionization, b) ~1 MV voltage applied to the discharge, and c) the energy load of several kilojoules deposited in a relatively short, ≤300 ns, time interval. The first x-ray preionized laser with such parameters is under construction at the ATF. Fig.3 shows the principal optical diagram of the ATF TWps CO_2 laser system.

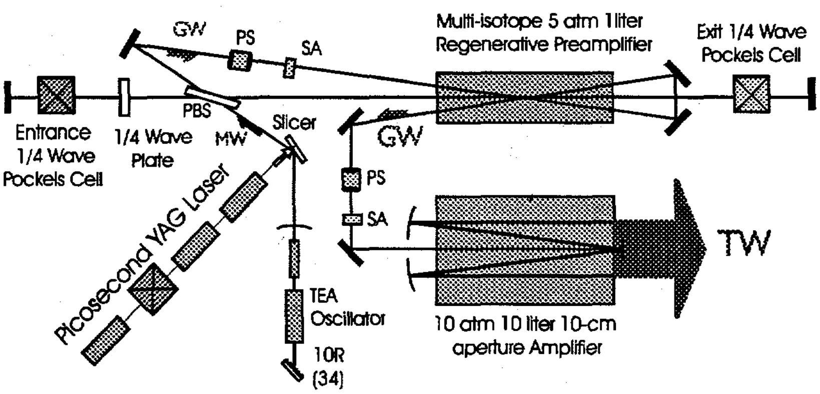

FIGURE 3. Optical diagram of the ATF TWps-CO_2 laser; PS - plasma filter; SA - saturable absorber; PBS - polarizing beam splitter

The 1 MW, 100 ns pulse produced by a 1-atm CO_2 laser oscillator is sliced at a semiconductor switch controlled by the picosecond Nd:YAG laser. The high power will be attained via regenerative amplification and four additional passes through the preamplifier followed by three passes in the 10-atm, 10-l final amplifier with the beam expansion to its full 10-cm aperture.

This diagram looks relatively simple to anyone who is familiar with the T^3 laser designs. There is a principal physical reason for this. Because of the strong optical nonlinearity of solids, the high laser energy can not be extracted directly in a picosecond pulse. The relatively sophisticated chirping technique should be implemented. This technique requires diffraction stretchers and compressors of the laser pulse. As a result, the optical damage of diffraction gratings becomes the primary limiting factor for this technology. The gas medium of the CO_2 laser is free from this limitation; thus a picosecond laser pulse may be amplified directly.

Table 1 serves to compare the main physical parameters of solid-state and CO_2 lasers. Because of the broader gain bandwidth in the solid state lasers, as short as 10 fs laser pulses can be produced whereas the CO_2 laser pulses are limited to ~1 ps the shortest. However, such pulse duration is sufficient for the critical applications that we consider below.

A gain cross-section per ion or molecule is comparable for both types of lasers. About ten times higher concentration of active ions in solid matter than the CO_2 molecules in a gas results in a ten times higher gain for solid state lasers. In addition, ten times higher photon energy makes the specific stored energy in solid state lasers about hundred times higher. However, the large volume of a gas laser makes the total stored energy per CO_2 laser stage similar or higher than for a big-aperture slab solid state amplifier.

Because of the ease of the heat removal by fast gas exchange in the CO_2 laser, it is potentially capable of high repetition rates that are difficult to attain with massive glass or crystal active elements. This will be important for future advanced particle accelerators. For example, CO_2 laser pulses of ~1 ps duration, 1 J energy, and 10 kHz repetition rate may be required to drive the $e^{\pm}\Rightarrow\gamma$ converter of the future 5 TeV c.m. collider. Relatively compact ~10 l discharge, high-pressure, fast-flow CO_2 lasers operating at a ~100 Hz repetition rate may approach this requirement when the energy stored in the laser medium is extracted by a train of pulses of 1 ps length each following at a ~1 ns period. Such a regime looks not just feasible but also quite efficient, permitting extraction of a good portion of the stored CO_2 laser energy. Overall electric efficiency of the laser may approach 20% as has been demonstrated for the long-pulse CO_2

lasers pumped with the e-beam sustained discharge. An additional straightforward way to increase the efficient pulse repetition rate is recycling of the laser power in storage cavities [4].

2. TWps-CO_2 LASER APPLICATIONS IN HIGH ENERGY PHYSICS

2.1. Laser Wakefield Accelerators and e^--e^+ Colliders

High-gradient laser acceleration is a fast advancing area of the high energy physics research. Among the known laser acceleration techniques, the LWFA method [5] is considered to be the most reliable approach. It is based on the ponderomotive charge separation and a relativistic wake formation when the propagating laser pulse duration is in resonance with the plasma oscillation. The amplitude of the accelerating field, E_a, due to the charge separation in a plasma wave reaches

$$E_a[V/cm] = \left(a^2/\sqrt{1+a^2}\right)\sqrt{n_e}\left[cm^{-3}\right], \quad (1)$$

where n_e is electron density in plasma, and a is the dimensionless laser vector-potential

$$a = eE_L / mc\omega = 0.3E_L[\text{TV/m}]\lambda[[\mu\text{m}]. \quad (2)$$

From Eqs.(1) and (2) we see that a 10-µm CO_2 laser is capable of producing an accelerating gradient at least 10 times higher than the 1-µm laser of the same intensity. This is due to the stronger ponderomotive potential of plasma electrons oscillating in a lower-frequency electromagnetic field.

TABLE 1.
Characteristics of Solid State and CO_2 Lasers

PARAMETER	Solid State	10-atm CO_2
Bandwidth (THz)	5-50	1
Cross section ($\times10^{-20}$ cm^2)	1-30	5
Gain (%/cm)	~50	3-4
Saturation energy (J/cm^2)	1-20	0.5
Stored energy (J/cm^3)	1	0.01
Active volume (cm^3)	10-100	10,000
Maximum efficiency (%)	10	20
Average power (W)	10	10,000

Using 1-µm laser pulses of a shorter duration and at correspondingly higher plasma densities help to compensate for the low ponderomotive strength and attain high acceleration gradients. However, the maximum number of particles per bunch, N_e, at the limit when the bunch self-field does not effect the plasma wake structure, drops proportionally to the plasma wavelength: $N_e \propto \lambda_p \propto n_e^{-1/2}$. This becomes especially important when we consider a prospective design of the LWFA stages for the future TeV e^--e^+ collider [6] where the most critical characteristic, luminosity

$$\Lambda = N_e^2 f\zeta / 4\pi\sigma_\perp^2, \quad (3)$$

(where ζ is a number of bunches per train, f is the linac repetition rate, and $\sigma_\perp$ is the e-beam cross-section at the interaction point) is proportional to N_e^2.

Another potential advantage of using a longer period plasma wave is that it facilitates fitting of the electron bunch inside the small portion of the wake period thus ensuring the good beam quality (small energy spread and emittance). For example, at τ_L=1 ps and the resonance plasma wavelength λ_p=600 µm the desirable electron bunch duration is $\tau_b \leq 200$ fs. Contemporary photocathode RF guns tend to approach these requirements. In particular τ_b=370 fs electron bunches of 2.5×10^8 electrons, $\Delta p/p = 0.15\%$, and ε_n=0.5 mm.mrad have been demonstrated with the ATF photocathode RF gun [7].

Provided methods of plasma channel formation are available, compact (~1 m) LWFA of several GeV energy driven with the technically feasible ~50 TW lasers may become a reality. Staging of such accelerators permits the new generation of TeV-class e^--e^+ colliders less than 1 km long.

2.2. Table-Top Laser Synchrotron Source

Synchrotrons equipped with wiggler magnets are the sources of x-ray fluxes at a level of 10^{18} photon/sec. According to another approach to a relatively compact high-brightness x-ray generator called laser synchrotron source (LSS), the laser beam acts on relativistic electrons as an electromagnetic wiggler with a period 10^4-10^5 times shorter than the magnetic undulator. Thus, LSS produces proportionally heavier photons than a conventional synchrotron source operating at the same e-beam energy. Similarly, LSS permits significant downsizing of the electron accelerator.

A combination of a high-gradient LWFA with LSS may open a route to table-top wakefield LSS operating in x-ray and gamma regions. Proof-of-principle table-top LSS may be realized at the ATF using the 5-TW CO_2 laser and a 5 MeV photocathode electron gun. The CO_2 laser beam is split into two beams that serve to drive both LWFA and LSS as is shown in Fig.4. PIC simulations predict 250 MeV acceleration when a 4 TW CO_2 laser beam is focused into the waveguide with parameters shown in Table 2 [8]. At the exit of the waveguide, electrons accelerated in the plasma wake field interact with the second CO_2 laser beam, generating an x-ray flux orders of magnitude above numbers obtained with conventional synchrotron light sources.

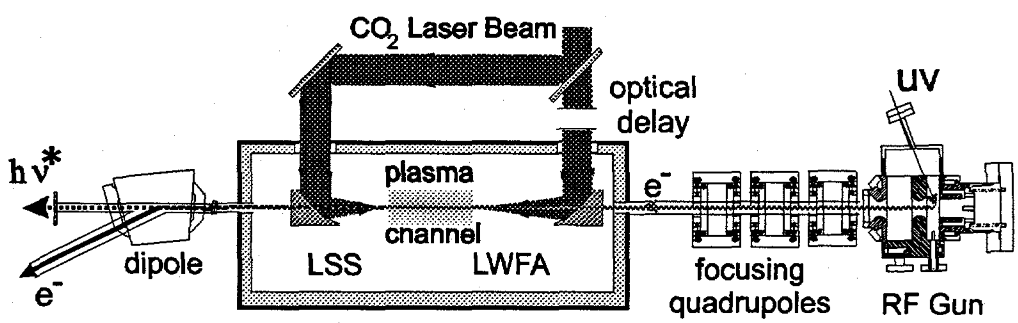

FIGURE 4. Table-top laser wakefield x-ray source

TABLE 2. Design Parameters for Table-Top LSS

LWFA	
Initial Electron Energy [MeV]	5
Bunch Charge [nC]	0.1
Bunch Duration FWHM [fs]	300
Laser Peak Power [TW]	4
Laser Pulse Duration [ps]	3
Plasma Density [cm^{-3}]	3.5×10^{16}
Channel Radius [μm]	60
Channel Length [cm]	4
Energy Gain [MeV]	250

LSS	
Laser Peak Power [TW]	1
Laser Pulse Duration [ps]	3
Laser Focus Radius [μm]	30
X-ray Photon Energy [keV]	470
Angular Spread [mrad]	0.1
Spectral Bandwidth [%]	0.2
X-ray Pulse Duration [fs]	300
X-ray Photons per Pulse	3×10^9
X-ray Peak Flux [photons/s]	10^{22}

2.3. Gamma and Positron sources for Linear Colliders

By Compton backscattering of the laser photons from the TeV electron beam, a high brightness TeV photon beam can be created. It opens an opportunity to study a variety of interaction processes by colliding e^-, e^+ and γ beams in any combination and at independently controlled polarization.

The expression for the maximum gamma photon energy for linear Compton backscattering is

$$\hbar\omega_\gamma = (x/x+1)E_e, \tag{4}$$

where E_e is the electron energy, and $x = 4E_e\hbar\omega/m^2c^4$. At $x>>1$, the Compton photon energy approaches the electron energy, $\hbar\omega_\gamma \approx E_e$. For CO_2 laser, $x=1$ at $E_e=0.5$ TeV. Thus, the long wavelength of the CO_2 laser used for the $e^\pm \Rightarrow \gamma$ converter at $E_e=2.5$ TeV does not degrade ω_γ to compare with shorter wavelength lasers. Capable of high average power and delivering ten times more photons than solid state lasers of the similar energy, CO_2 lasers permit ultra-high intensity γ-sources.

The strong requirement to the laser wavelength is set by rescattering of gamma photons on the laser beam into pairs through the reaction $\gamma+\lambda \Rightarrow e^-+e^+$. This occurs when $\omega\omega_\gamma > m^2c^4/\hbar^2$. Based on this condition, the optimum laser wavelength is derived: λ[μm]=4.2E_e[TeV]. Thus, for the 2.5 TeV collider the laser with λ=10.5 μm is the optimum choice.

Lasers may be used also in polarized positron sources for e^--e^+ collider. Here, the backward Compton scattering serves as an intermediate process followed by pair production on a target. Polarization of the produced particles is controlled by the input laser beam. Picosecond CO_2 lasers have been selected as the optimum choice for the Japan Linear Collider [9]. Both applications described in this paragraph are illustrated by Fig.5.

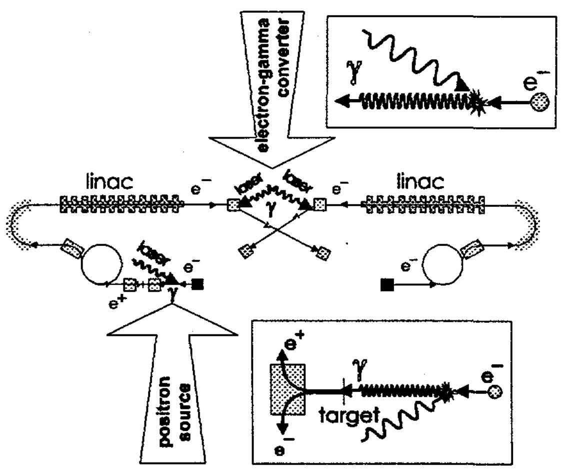

FIGURE 5.
Electron-gamma converter and polarized positron source for future electron-positron collider

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