EMERGING TERAWATT PICOSECOND CO_2 LASER TECHNOLOGY AND POSSIBLE APPLICATIONS IN ACCELERATOR PHYSICS

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Abstract

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

1 EMERGING TWps-CO_2 LASER TECHNOLOGY

An important physical parameter that enables generation and amplification of picosecond laser pulses is the gain spectral bandwidth.

Methods to produce picosecond and sub-picosecond CO_2 laser pulses have been developed. One of them is semiconductor optical switching [1]. Using this method, subpicosecond slices out of a multi-nanosecond CO_2 laser output may be produced using conventional mode-locked solid-state laser.

Pressure broadening of the CO_2 gain spectrum at ~10 atm into a 1 THz wide quasi-continuum permits amplification of 0.5 ps laser pulses. Note that gas lasers are free from optical nonlinearity. This permits direct amplification of multi-terawatt λ=10 μm laser beams without a sophisticated pulse chirping technique which is necessary for terawatt solid state lasers.

For a τ_L=1 ps pulse propagating in a 10-atm amplifier, the estimated small-signal gain is 3-4%/cm and the extractable specific energy is ~20 mJ/cm^3. Taking into account that the total discharge volume may exceed 10 *l*, the possibility of extraction of as much as 100 J of energy in a picosecond pulse from a reasonably compact CO_2 laser amplifier looks realistic. However the damage threshold of the output window that is at the level of 0.5 J/cm^2. For an optical window of the ~100 cm^2 size, the extractable energy is 30-50 J which still permits ~30 TW peak power at a 1-ps laser pulse duration.

Thus, to attain 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 laser with such parameters is under construction at the Brookhaven ATF.

Fig.1 shows the principal optical diagram of the ATF TWps CO_2 laser system. 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 [2].

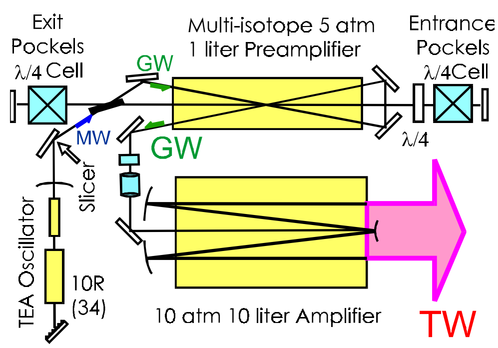

Figure 1: Optical diagram of the ATF TWps-CO_2 laser

The ATF laser, besides its role in user's experiments, will serve as a test bench for proof-of principle evaluation of the TWps-CO_2 technology for such strong field physics applications as high-gradient laser accelerators and high-intensity Compton x-ray sources. For that purpose, ATF also provides a high-brightness 50-MeV electron beam from a photocathode RF linac synchronized within subpicoseconds to the CO_2 laser pulse.

2 LASER WAKEFIELD e^--e^+ COLLIDER

Progress in the exploration of particle interactions relies upon the development of a new-generation of accelerators on a TeV energy scale. One of the prospective approaches is a linear e^--e^+ collider based on a high-gradient laser acceleration. The enthusiasm that drives research in this area is based on ultra-high electric fields attainable upon the tight focusing of terawatt laser beams.

This may permit reduction of the accelerator length by orders of magnitude.

Among the known laser acceleration techniques, the laser wakefield acceleration (LWFA) [3] is considered as the most promising. The LWFA method is based on the ponderomotive charge separation and a relativistic wake formation when a short laser pulse propagates in underdense plasma. The amplitude of the accelerating field, E_a, due to the charge separation in a plasma wave is

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

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

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

From Eqs.(1) and (2) we see that $E_a \propto \lambda^2$ for a<<1 and $E_a \propto \lambda$ for a>>1. This is due to the stronger ponderomotive potential of plasma electrons oscillating in a lower-frequency electromagnetic field. There are still tradeoffs to attain higher E_a with short-wavelength lasers via tighter laser focusing and using higher n_e. The analysis of two options to build the 2.5 TeV multi-stage plasma-channeled LWFA linac using CO_2 or a solid state lasers is presented in Table 1. Both design options are aimed to attain a luminosity $\Lambda=10^{35}$ cm^{-2}s^{-1} [4] defined as

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

where N_e is the number of particles per bunch, 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.

The parameters entering Table 1 are chosen according to the following prime considerations:

1. The 50 TW peak laser power foreseeable with state-of-the art laser technology, and the laser pulse duration - close to the experimentally demonstrated minimum.
2. The plasma channels are filled with a 100% ionized hydrogen at the density $0.5n_e$. The normalized emittance of the electron beam at 2.5 TeV due to gas scattering described by Highland formula [5] is:
$$\varepsilon_n[m.rad] \approx 3\times10^{-15}\left(n_e\left[cm^{-3}\right]\Big/E_a^2[MeV/m]\right). \qquad (4)$$
3. The channel length for every accelerator stage is ~$30z_0$, where $z_0=\pi r_L^2/\lambda$ is the Rayleigh length. A 20 cm long evacuated dead space is assumed between the accelerating channels. Note that optics of the same focal length are used for both lasers.
4. The maximum number of particles per bunch is calculated under the condition that space charge field of the electron bunch does not effect the wakefield structure: $N_e \le n_e\left(c/\omega_p\right)^3$.

We see that both design approaches illustrated in Table 1 demonstrate the LWFA capabilities to attain the desired 2.5 TeV electron energy in a compact multi-stage accelerator. However, the calculated requirements to the laser driver for two cases are essentially different.

Table 1. Prospective Multi-Stage 2.5 TeV LWFA

Laser Parameters		
Laser wavelength, λ [μm]	10	1
Energy [J]	50	5
Pulse length, τ_L [ps]	1	0.1
Power, P [TW]	50	50
Focal spot radius, r_L [μm]	300	30
Laser field, E_L [TV/m]	0.4	4
Dimensionless laser strength, a	1.3	1.3
Repetition rate. f [kHz]	0.2	20
Average power [kW]	10	100
Wakefield Parameters		
Plasma density, n_e [cm^{-3}]	3×10^{15}	3×10^{17}
Plasma wavelength, λ_p [μm]	600	60
Acceleration gradient, E_a [GeV/m]	4.5	45
Pump depletion length [cm]	280	28
Phase detuning length [cm]	230	23
Assumed channel length [cm]	100	10
Energy gain per stage [GeV]	4.5	4.5
Collider Parameters		
Electrons/bunch. N_e	3×10^9	3×10^8
Number of bunches per pulse, ζ	3	3
ε_n due to gas scattering [m.rad]	4×10^{-7}	4×10^{-7}
$\sigma_\perp$ at β*=5 μm focus, [Å]	7	7
Luminosity, Λ [cm^{-2}s^{-1}]	10^{35}	10^{35}
Bunch repetition rate, ζf [kHz]	0.6	60
Number of stages	555	555
Total length [m]	666	166

With the 1-μm laser, the short τ_L results in a proportionally small λ_p and N_e. Then, in order to satisfy the high luminosity requirement, the laser repetititon rate and, hence, the average output power increase quadratically. This becomes orders of magnitude beyond any reasonable expectation for picosecond solid state laser technology and does not fit into the anticipated wall-plug power limits. On the contrary, the parameters specified for the 10-μm laser look achievable for TWps-CO_2 lasers.

Another potential advantage of using a longer period plasma wave is the ease in producing the injected electron bunch which is short enough to fit 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 \le$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 [6].

3 X-RAY AND GAMMA SOURCES BY COMPTON SCATTERING OF CO_2 LASER BEAMS

By Compton scattering 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 Compton backscattering is

$$\hbar\omega_\gamma = (x/x+1)E_e, \quad (5)$$

where E_e is the electron energy, and $x = 4E_e\hbar\omega/m^2c^4$. At x>>1, $\hbar\omega_\gamma \approx E_e$. For CO_2 laser, x>1 at E_e>0.5 TeV.

A requirement to the laser wavelength for the $e^\pm \Rightarrow \gamma$ converter is set by rescattering of gamma photons on the laser beam into pairs through the reaction $\gamma+\lambda \Rightarrow e^- + e^+$. This occurs when when $\omega\omega_\gamma > m^2c^4/\hbar^2$. Based on this condition the optimum laser wavelength is derived:

$$\lambda[\mu m]=4.2E_e[TeV] \quad (6)$$

Then, the laser with λ=10.5 μm becomes the optimum choice for the 2.5 TeV collider.

For τ_L=1 ps, probability of the $e^\pm \Rightarrow \gamma$ conversion,

$$\chi = \sigma_c \, \mathrm{E}_L / \hbar \, \tau_L c^2, \quad (7)$$

where $\sigma_c = 1.9\times10^{-25}$ cm^2 is the Compton scattering cross-section, reaches unity at the laser pulse energy $\mathrm{E}_L \approx 1$ J [7].

The laser pulse repetition rate should match that of the e^--e^+ collider. The TWps-CO_2 laser technology is envisioned to provide the laser source delivering picosecond pulses of a 1 J energy at a several kW of average power to satisfy the requirements of the γ-γ collider. Relatively compact ~10 *l* discharge, high-pressure, fast-flow CO_2 lasers operating at a ~100 Hz repetition rate may serve this purpose when the energy stored in the laser medium is extracted at the wall-plug efficiency approaching 10% by a train of a hundred pulses of a 1 ps length each following at a ~1 ns period. A feasibility of building a solid state laser operating in a similar regime has been considered in Ref. [8].

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 or via rescattering on laser photons. Polarization of the produced particles is easily controlled by the input laser beam. Picosecond CO_2 lasers are the optimum choice for this application as well due to the high average power and having ten times more photons per joule than solid state lasers. The projected positron source for the Japan Future Collider at KEK [9] will employ a hundred 1.5 kW CO_2 lasers with 150 Hz repetition rate and 50 ps pulse duration. This project appears to become the biggest utilization of CO_2 lasers in fundamental science.

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 higher energy photons than a conventional synchrotron source operating at the same e-beam energy. Therefore, LSS permits significant downsizing of the electron accelerator.

A combination of a high-gradient LWFA with LSS opens up the possibility of a compact wakefield LSS operating in x-ray and gamma regions. Table-top LSS, generating peak x-ray flux orders of magnitude above conventional synchrotron light sources, may be realized at the ATF using the 5-TW CO_2 laser and a 5 MeV photocathode electron gun (see Table 2) [7].

The ATF laser, designed for proof-of-principle experiments, is limited to the 0.1 Hz repetition rate. The above mentioned possibility of a high repetition rate multi-pulse TWps-CO_2 lasers makes it possible for ~10 kHz compact LSS to approach the time-aweraged photon flux of conventional synchrotron light sources.

Table 2. Design Parameters for Table-Top LSS

LWFA	
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
Acceleration gradient [GV/m]	6
Energy Gain [MeV]	50-250
LSS	
Laser Peak Power [TW]	1
Laser Pulse Duration [ps]	3
Laser Focus Radius [μm]	30
Tunable X-ray Photon Energy [keV]	4.7-1000
X-ray Pulse Duration [fs]	300
X-ray Photons per Pulse	3×10^9
X-ray Peak Flux [photons/s]	10^{22}

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