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THE FIRST PICOSECOND TERAWATT CO_2 LASER AT THE BROOKHAVEN ACCELERATOR TEST FACILITY

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Abstract

The first terawatt picosecond CO_2 laser will be brought to operation at the Brookhaven Accelerator Test Facility in 1998. System consists of a single-mode TEA oscillator, picosecond semiconductor optical switch, multi-atmosphere. We report on design, simulation, and performance tests of the 10 atm final amplifier that allows for direct multi-joule energy extraction in a picosecond laser pulse.

1. Introduction

Presently, 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 newly emerging 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 primarily due to the inherently low efficiency of the thermal diffusion cooling of the solid active elements. Much more efficient heat exchange may be implemented in the fast-flow gas lasers. The demonstrated high output energy and power of molecular and excimer 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 [1, 2]. However, kilojoule lasers are bulky and 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 femtosecond pulse duration turns out to be a prerequisite for the successful use of lasers in high energy physics and many other advanced scientific applications.

The concept of picosecond terawatt CO_2 lasers has been outlined some time ago [3, 4]. However, conclusive steps in this direction have not been taken until the project on the First PIcosecond TERawatt (PITER I) CO_2 laser initiated at the Brookhaven Accelerator Test Facility (ATF). Today, PITER I is close to completion and will become available for the ATF users in 1998. It is relevant to note at this point that the ATF is a DOE user's facility. That means that anybody who is interested to set up an experiment using technical capabilities of the ATF may come with a proposal. Upon approval, applicants may get a time and space for doing their experiments.

What kind of experiments may be conducted at the ATF is illustrated by Fig.1 that shows the main ATF components: linac, Nd:YAG and CO_2 lasers. Presently, the 100 ps 10 GW CO_2 laser is in operation. The 10 ps pulses of 3 TW power will be obtained after installation of a new high-pressure big-volume laser amplifier in 1998.

The mode-locked solid state laser helps to solve the problem of generating a picosecond 10-μm pulse by switching a semiconductor optical shutter. The same laser produces electron bunches at a photocathode gun which are accelerated by the RF linac to the 50 MeV energy. This permits automatic synchronization of the amplified CO_2 laser pulse with a picosecond electron bunch for interaction experiments including laser acceleration, Compton scattering, etc.

The rest of the paper is organized as follows. In Section 2 we review the issues relevant to operation of a CO_2 laser in the nontraditional picosecond regime. In Section 3 we describe the PITER I design. In Section 4 we will look into further prospects: what can we expect in the long run from picosecond and subpicosecond CO_2 technology in view of its application to high-energy physics.

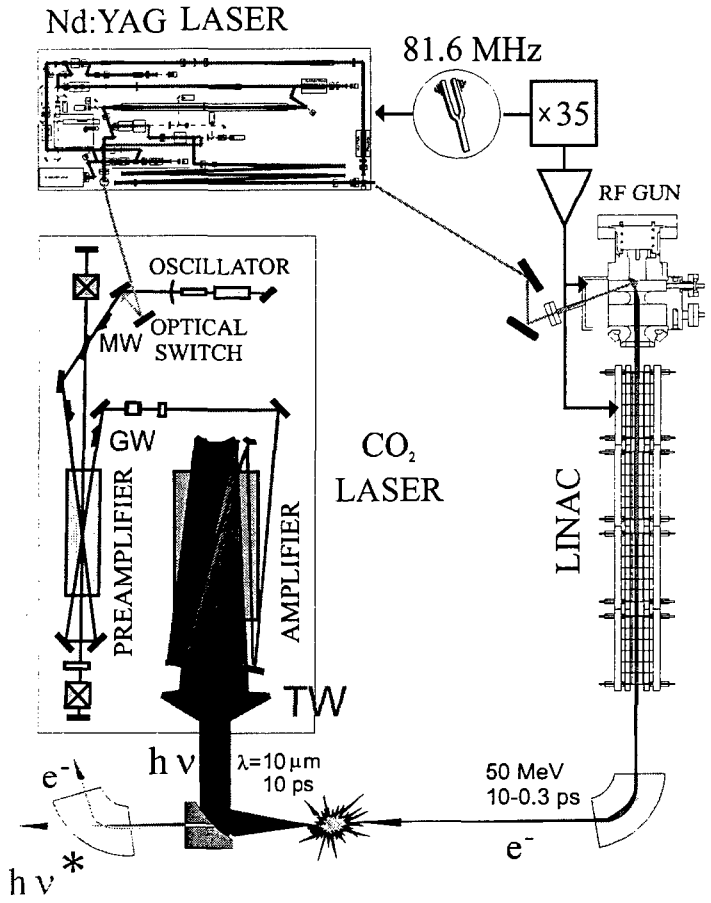

Fig.1 Principle diagram of the ATF laser system and linac with subpicosecond synchronization for the electron-photon interaction experiments.

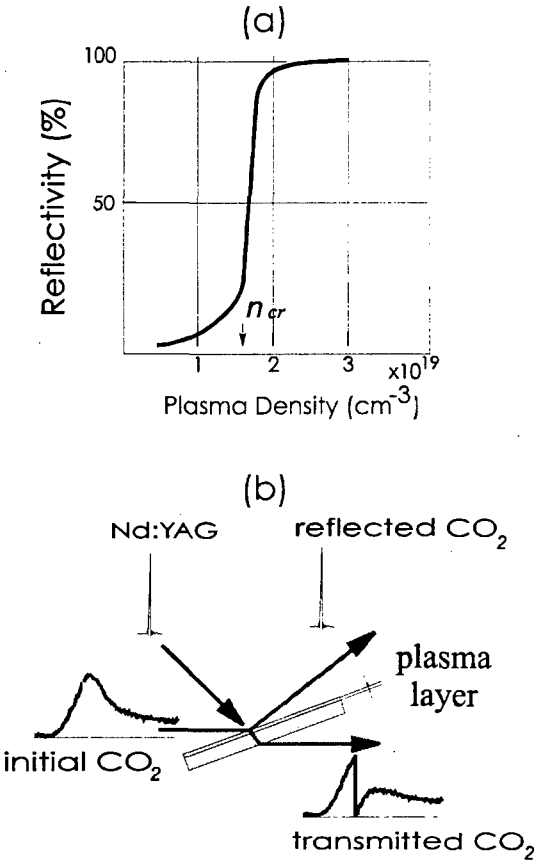

Fig.2 Principles of semiconductor optical switching: a) reflectivity of Brewster Ge window versus surface free-electron density [5]; b) transition reflection from semiconductor optical switch.

2. Bandwidth limitations of the CO_2 Laser Technology

A physical parameter that enables generation and amplification of picosecond laser pulses is the spectral gain bandwidth. In solid state lasers, radiation transitions in outer electron shells of active ions are broadened to 5-50 THz due to the field perturbation 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 pulses have been demonstrated [6].

Illustrated in Fig.2 the optical switching process works as follows. Nd:YAG pulse having a photon energy above the band gap of germanium creates a cold electron-hole plasma in the surface layer. When the plasma reaches the critical density the refractive index becomes imaginary, and Ge Brewster window, which is normally transparent to the 10-μm radiation, turns to a metal-like mirror. After the control pulse terminates, the drop of reflection from 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. Practical scheme shown in Fig. 3 is a little bit more complex, but the principle is the same.

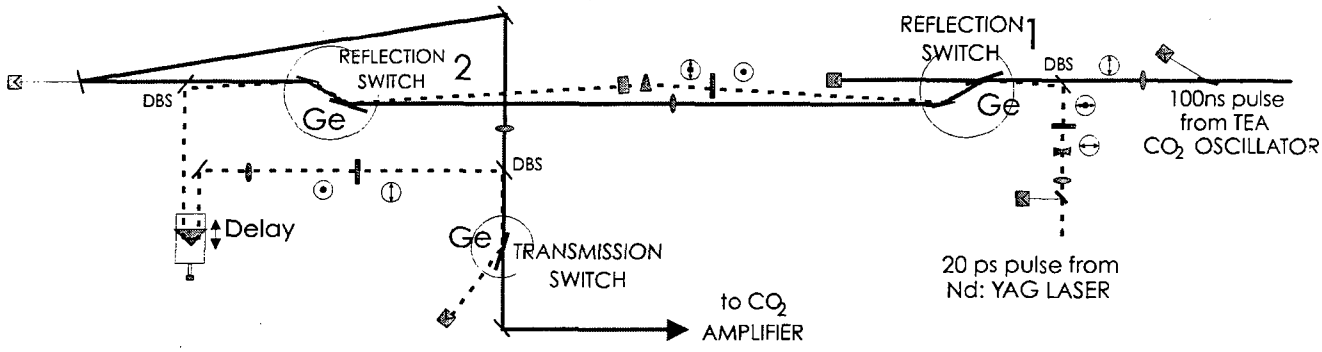

Fig.3 Three-stage ATF slicing system

We know how to produce a short pulse. However, there is another problem: how to amplify it. The restricted bandwidth in the molecular laser is the limitation to the short pulse amplification. When a short pulse propagates in a gas with a periodic modulated rotational spectrum, the nonuniform spectral gain modifies the spectral envelope of the pulse. The intensity envelope, related to the spectrum by the inverse Fourier transform, will be correspondingly reshaped. The pulse splits into a train of pulses. The period in this train corresponds to the frequency interval between the centers of rotational lines, which is 18 ps (see Fig.4 a-b).

Smoothing of the molecular spectrum via pressure broadening helps to minimize the laser pulse distortions (see Fig.4 c-d). An alternative way to achieve gain smoothing is to reduce the spectrum modulation period using a CO_2 gas mixture with a combination of the isotopes O^{16} and O^{18}. Due to isotopic shifts, the combined spectrum has 4-times denser rotational line structure than with a regular CO_2 molecule. Theoretical limit to the pulse duration defined by the total 1 THz bandwidth of the 10P vibrational band of the CO_2 transition is 0.5 ps.

However, it is still not the bottom limit for CO_2 laser pulse shortening. Taking a combination of all available isotopes of O and C a pressure broadened continuum can be produced which extends over spectral region with the 7 THz bandwidth (see Fig.5). Then amplification of as short as 100 fs pulse becomes possible [4]. Another method of CO_2 laser pulse shortening uses pulse chirping in a gas [4, 7]. Physics of this process is rather straightforward. Intense laser pulse propagating in a gas produces ionization. As a result the refraction index is changing and a tail of the pulse propagates at a higher speed than its front.

After a propagation over a certain distance or in the dispersive medium the pulse will shorten. This effect has been observed already by P. Corkum inside the laser amplifier [7]. He considers that this process may be organized in a more controlled fashion in a gas-filled hollow fiber [8].

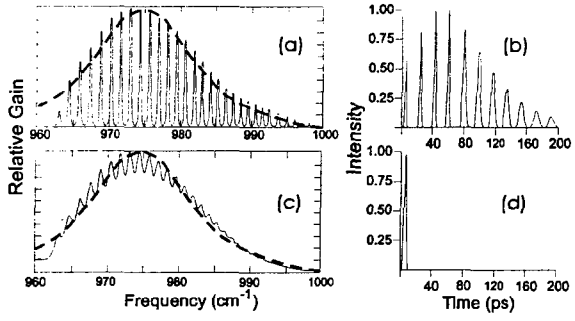

Fig.4 . Picosecond CO_2 laser pulse amplification:
a) CO_2 gain spectrum at 1 atm (dashed line shows spectral envelope of 1 ps CO_2 pulse); b) 1 ps pulse splits into a train after propagation through 1 atm laser amplifier (simulation); c) CO_2 gain spectrum at 10 atm matches 1 ps pulse; d) 1 ps pulse is amplified in 10 atm laser amplifier without distortions.

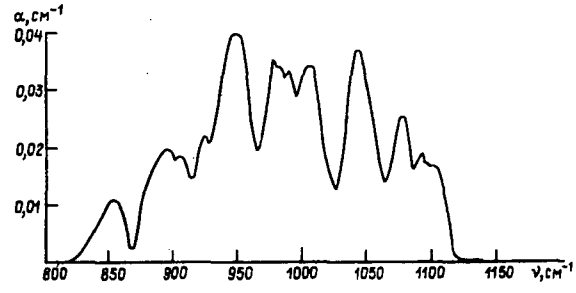

Fig.5 Pressurized mixture of CO_2 molecules composed of isotopes C^{12}, C^{13}, C^{14}, O^{16}, O^{18} has a gain bandwidth (7 THz) sufficient to amplify 100 fs laser pulses [4].

3. Design and Status of Picosecond Terawatt CO_2 Laser System PITER I

The principle optical diagram of the ATF CO_2 laser system is shown in Fig.1. The oscillator and semiconductor switch supply a seed pulse into the regenerative preamplifier with the active discharge volume of 1.2 liters (optical aperture 2×5 cm^2, discharge length 1.2 m). Extracted by Pockels cell at several millijoules, the laser pulse is redirected for additional passes through the same discharge cell to acquire up to 1 J energy.

Photo of the open preamplifier discharge cell is shown in Fig.6. Two 60 cm long high-voltage electrodes are positioned under the ground mesh electrodes. Surface discharges, sliding along the sapphire tubes, serve as the sources of the UV ionization. The sapphire tubes are assembled on the cell lid and placed on top of the electrode assembly. UV photons penetrate through the ground mesh into the discharge region producing initial ionization of the gas mixture. Energized with the 150 kV discharge, the preamplifier can operate at up to 5 atm pressure. To amplify picosecond pulses, it will be filled with the isotopic gas mixture. A saturable absorber and a plasma shutter positioned in the preamplifier output beam serve to increase the signal-to-noise contrast and prevent self-excitation and radiation ringing in the laser system.

The terawatt power will be attained in the 10-atm, 10-liter final amplifier. The amplifier for PITER I has been designed and manufactured by Optoel Co., St. Petersburg, Russia. Pictures taken at the Optoel test stand and shown in Fig. 9-11 illustrate the design and dimensions of the amplifier discharge cell which is the primary component of the amplifier. The discharge cell is manufactured of stainless steel and is capable to withstand high pressure and voltage. The design parameters and results of preliminary tests of the amplifier are compiled in Table 1.

In Fig.7 we see a cross-section diagram of the amplifier discharge cell. To maintain a uniform discharge in a big volume and at a high pressure, a strong penetrating ionizer was needed. The UV ionization would be inefficient in this case due to the short absorption length in high-pressure molecular gases. From the other hand, using the electron beam as a preionizer requires relatively fragile thin foils which are unreliable at the high pressure.

TABLE 1.
Amplifier design parameters

Pressure	10 atm
Gas Mixture CO_2:N_2:He	1:0.5:8.5
Interelectrode Distance	8 cm
Electrode length	1 m
X-Ray Pulse Length	2 μs
X-Ray Dose	0.1 R
Discharge Voltage	1 MV
Stored Electric Energy	5 kJ
Discharge Peak Current	90 kA
Current Pulse FWHM	500 ns
Pulse Front	200 ns
Gain Coefficient	3%/cm
Saturation Energy	0.5 J/cm^2
Input Energy	30 mJ
Number of Passes	4
Output Aperture	80 cm^2
Output Energy	30 J
Laser Pulse Duration	10 ps
Peak Power	3 TW
Repetition Rate	0.1 Hz

For the PITER I preamplifier we use an intermediate approach - an x-ray preionizer. Inside the high-pressure cell there is a high-vacuum cell of the 100 kV electron gun with the 10×100 cm^2 carbon fiber corona cathode. The electrons, accelerated up to 100 keV, are stopped at the relatively robust 80 μm thick titanium foil window where they transfer the energy to the x-rays. The x-rays penetrate through the foil and the mesh ground electrode into the interelectrode space. The x-ray dose 0.1 R, shown in the Table 1, is measured just after the mesh electrode. The x-ray dose drops several times over the 10 cm interelectrode distance due to a geometric spread of the x-ray flux.

1 MV pulse is applied to the discharge and a several kilojoule energy load is delivered in a short time interval, because the uniform discharge breaks down to arcing after about 300 ns. To achieve the energy deposition at such relatively short time interval, the impedance-matched pulse-forming network (PFN) is installed between the discharge cell and a conventional 10-stage Marx generator from Maxwell Laboratories as is shown in Fig.8. The PFN consists of water capacitors with the commutation water spark gap. Immersed into water, stainless steel electrode plates of the PFN are adjustable to sharpen the leading front and shorten duration of the voltage pulse delivered to the amplifier discharge.

Further optimization of the amplifier configuration and gas mixture is under way. However, already achieved 3%/cm optical gain is the encouraging result never demonstrated previously in the x-ray preionized CO_2 lasers of such a big volume and pressure. Four passes through the amplifier with the beam expansion to 10-cm aperture will be arranged using mirrors internally mounted in the discharge cell.

PITER I is intended for proof-of-principle experiments. For that purpose, it is sufficient to use a relatively simple low repetition rate laser. The laser will deliver one pulse in several seconds limited primarily by the amplifier power supply and a slow gas circulation through a catalyst. That helps to keep the amplifier relatively compact. As is seen on Fig.8, together with the pulsed power supplies, it occupies a space comparable to a regular size optical table.

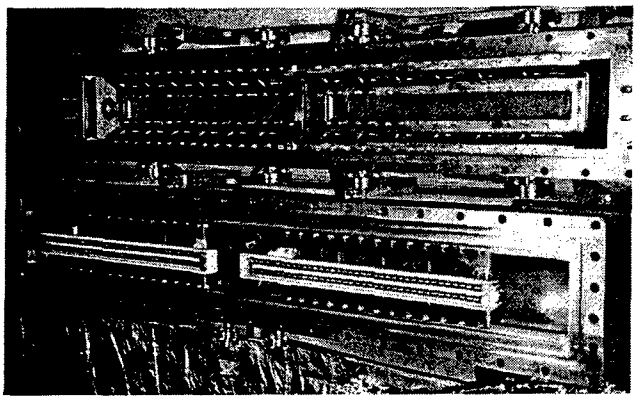

Fig.6 Photo of the opened preamplifier discharge cell

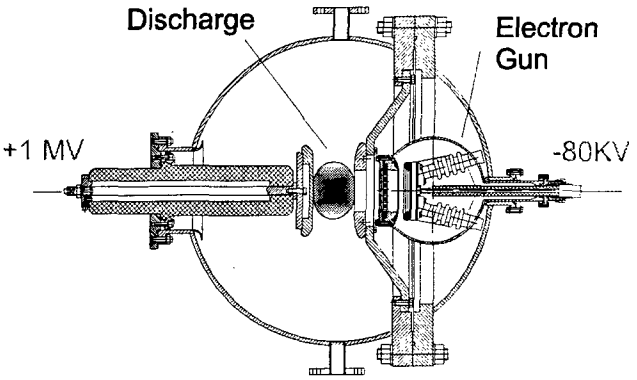

Fig. 7 Diagram of the amplifier cross-section

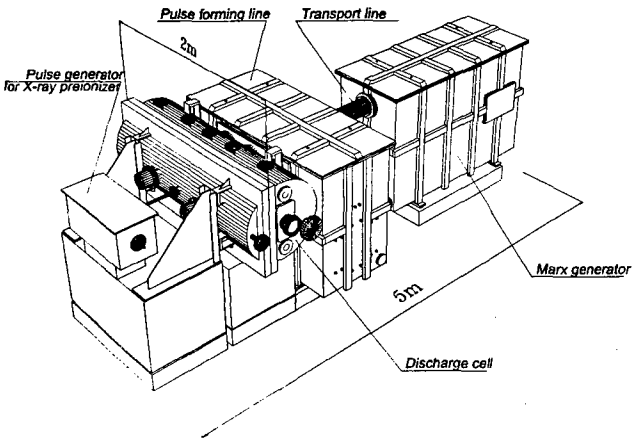

Fig.8 Diagram of the amplifier assembly

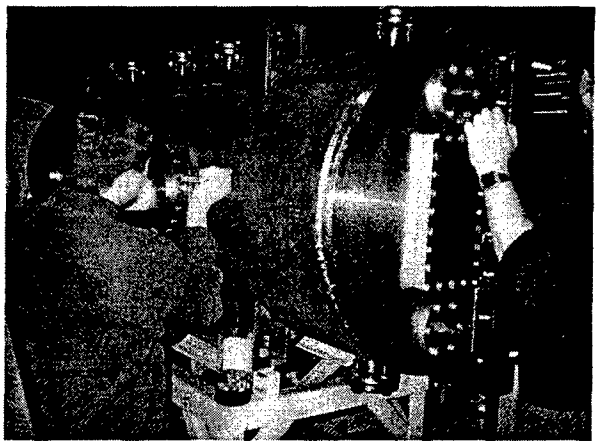

Fig.9 In preparation for pressure test of the amplifier discharge cell

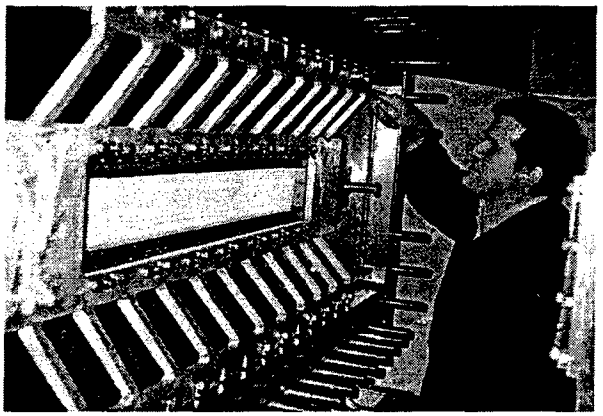

Fig.10 Alignment of ground mesh electrode (high-voltage electrode is behind the mesh)

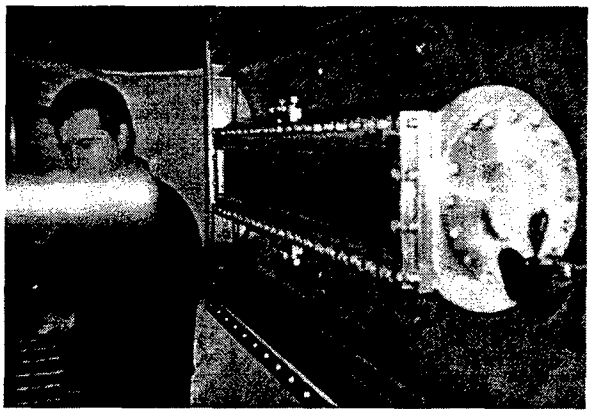

Fig.11 X-ray tube assembled inside the amplifier (technician is 5'8" tall)

4. Prospects of Terawatt Picosecond CO_2 Laser Technology for High Energy Physics Applications

The principle optical diagram of the TWps CO_2 laser system shown in Fig.1 looks relatively simple to anyone who is familiar with terawatt solid state laser designs. There is a physical reason to 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 pulse 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.

Let us compare other main physical parameters of solid-state and CO_2 lasers summarized in Table 2. We see that a gain cross-section per ion or molecule is comparable for both. About ten times higher concentration of active ions in a 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, a big volume of a gas laser makes the total stored energy per CO_2 amplifier 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 amplifier, it is potentially capable to high repetition rates that are difficult to attain with massive glass or crystal active elements. This may be important for future advanced particle accelerators. It is true that 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 or 100 fs the shortest. However, such pulse duration is sufficient for the critical applications that we consider today.

Table 2. Comparative characteristics of solid state and CO_2 lasers

PARAMETER	Solid State	10-atm CO_2
Bandwidth (THz)	5-50	1
Cross section (10^{-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
Average power (W)	1-10	100-1000

The prognosis about a possibility of picosecond CO_2 lasers with a kilowatt average power does not look over-optimistic if one looks into the prior achievements of this technology. Table 3 illustrates already demonstrated and practically attainable parameters of the CO_2 lasers. Note that the listed parameters have been obtained in different devices. For example, high pulse energy in Antares laser in Los Alamos [1] and short pulse in Canada by P. Corkum [8].

The prospective TWps-CO_2 laser parameters are given for laser devices of a similar discharge volume and optical aperture as the ATF laser. It is understood that scaling of the gas lasers permits modules of a bigger size and higher outputs. However, even medium size devices give a promise for attaining outputs of the order of several tens of TW and average power about several kW that may satisfy such advanced applications as future e^--e^+ and γ-γ colliders outlined in recent publications [9-11]. 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 [11]. 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 the 1 ps length, 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 [12].

TABLE 3. Demonstrated and projected cumulative characteristics of CO_2 lasers

PARAMETER	Demonstrated capabilities of CO_2 lasers	Emerging picosecond CO_2 lasers*
Min. pulse length	0.5 ps (theory), 0.8 ps (experiment)	1 ps
Efficiency	15-20% with e-beam sustained discharge	5% (single pulse), 10-20% (pulse train)
Energy per pulse	3 kJ (nanosecond pulse)	50 J (limited by window damage)
Peak Power	3 TW (Antares)	50 TW; (5 TW - short term, ATF)
Average power	50 kW (DC discharge)	10-50 kW
Repetition rate	100 Hz to RF (at several kilowatts of average power)	~1 kHz (limited by power supply, heat is removed by gas exchange)

* Parameters estimated for e-beam sustained laser module of a 10 *l* discharge volume with the 10×10 cm^2 output window

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