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## Gas Lasers for Strong-Field Applications

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# Gas Lasers for Strong-Field Applications

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**Abstract.** Atomic-, molecular- and excimer-gas lasers employ variety of pumping schemes including electric discharge, optical, or chemical reactions and cover a broad spectral range from UV to far-IR. Several types of gas lasers can produce multi-kilojoule pulses and kilowatts of average power. Among them, excimer- and high-pressure molecular lasers have sufficient bandwidth for generating pico- and femtosecond pulses. Projects are underway and prospects are opening up to bring ultrafast gas laser technology to the front lines of advanced accelerator applications.

## 1. INTRODUCTION

A laser is a quintessential instrument for advanced accelerator research. Presently, solid-state lasers based on chirped pulse amplification (CPA) have a dominant position. Indeed, talking about lasers, researchers nearly always have in mind a CPA laser.

Meantime, let us remember that the first beatwave laser acceleration was demonstrated with a CO<sub>2</sub> gas laser [1], and since then the same laser has enabled other mechanisms of electron acceleration, namely inverse Cherenkov [2] and inverse FEL [3].

Also, the first and the only staged and monoenergetic laser accelerator experiment STELLA [4] was operated with the same laser.

In a closely related field, the strongest Thomson x-ray source also was attained with a CO<sub>2</sub> laser [5].

These accomplishments look quite remarkable, particularly after taking into account the unfavorable proportion of both theoretical and experimental efforts routed into gas-laser applications to advanced accelerator research, and that just two gas-laser facilities are operating for these kinds of experiments (at the UCLA and BNL).

The rationale for these observations is not to reinstate priorities or competing paths between solid-state and gas lasers but to back up my next statement: To realize the challenging goal of discovering sensible alternative solutions for particle accelerators, we shall take the best from both solid-state and gas-laser technologies and to push most likely ones to a higher level of performance. This objective justifies the purpose of this lecture: to raise awareness within the advanced accelerator community about the technical capabilities of gas lasers.

In general, gas lasers is a very broad subject. Atomic-, molecular- and excimer-gas lasers cover a spectral range from UV to far-IR. Some can produce beams of the kilowatts and even megawatts of average power with a wall-plug efficiency up to 70% (more than 100% for chemical lasers). Gas lasers employ a variety of pumping schemes including electric discharge, electron beams, optical and chemical pumping.

I will narrow the scope to those lasers that appear to be the most useful for such applications as novel electron and ion injectors and accelerators, x-ray sources based on Thomson scattering, and the like that are the core subjects of this meeting. All these

applications require lasers able to generate relativistically strong normalized fields  $a = eE/mc\omega > 1$  and operating at a high repetition rate.

Several ongoing gas-laser projects will be reviewed, giving special attention a picosecond CO<sub>2</sub> laser that proved to be a valuable tool for strong-field physics applications. Finally, I analyze possibilities for generating CO<sub>2</sub> laser pulses of petawatt peak power and a-few-cycles duration.

## 2. INITIAL COMPARISON BETWEEN SOLID-STATE AND GAS LASERS

I start by evaluating the core differences between CPA and gas lasers. The numbers shown in Table 1 are valid to an order-of-magnitude and may vary for different types of lasers, especially for different gas lasers. For a better certainty in these parameters, two examples of gas lasers are chosen. The first is a photolytic iodine laser the design of which is close to that of solid-state lasers. The second is a high-pressure CO<sub>2</sub> laser (10 atm) that appears to be the most promising among gas lasers for the purpose of this discussion.

TABLE 1. Typical Parameters of solid-state and gas lasers

PARAMETER	Solid State	Iodine Photolytic	10-atm CO <sub>2</sub>
Host matrix density (cm <sup>-3</sup> )	10 <sup>23</sup>	10 <sup>19</sup>	10 <sup>20</sup>
Active particle density (cm <sup>-3</sup> )	10 <sup>20</sup>	10 <sup>18</sup>	3×10 <sup>18</sup>
Photon energy (eV)	1	1	0.1
Stored energy (J/cm <sup>3</sup> )	5	0.2	0.05
Gain (%/cm)	~50	10	3-4
Active volume (cm <sup>3</sup> )	50	2,000	10,000
Output energy (J)	100	100	100
Bandwidth (THz)	5-50	0.01	1
Average power (kW)	1	1	10

Basically, all the differences between the gas and solid-state lasers start from the difference in material density, ~10<sup>19</sup> against ~10<sup>23</sup> cm<sup>-3</sup>. The percentage of doped active ions in a solid crystal or glass matrix is small compared with a dilution in a gas-laser mixture. Thus, there is just about a 10-100 times difference in the density of active ions, or atoms, or molecules, and ultimately, about 100 times in the amount of specific stored energy. The optical gain factor also differs by an order-of-magnitude. Together, this means that an active gas medium must be about 10 times longer and 100 times larger in a volume to produce comparable output energy. Fortunately, such scaling in size is quite possible with gases.

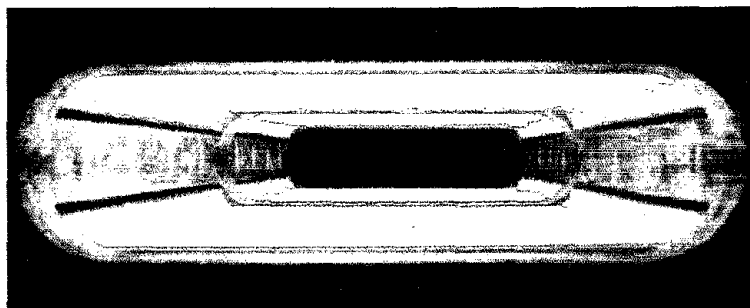
The most essential difference between solids and gases for generating ultrashort pulses lies in their bandwidth. In a dense solid lattice, the ion radiation line splits and broadens due to potential energy perturbation. Gas molecules are closer to their natural free state and typically generate linear spectra. However, at a high pressure, as in the

example shown in the last column of Table 1, the radiation lines become broadened due to molecular collisions and overlap into a continuum.

An important advantage of gas lasers is a relative ease of achieving high average power in the CW or in the high-repetition-rate regime. This is quite understandable because the key issue in attaining such regimes is the relief of the thermal load caused by pumping. In solids this can be done only via a relatively slow conductive heat transfer. In contrast, substituting a heated gas circulating in a closed loop through a heat exchanger readily solves the thermal problem.

To excite the laser action in solids, only optical radiation partially penetrating through the laser rod or disk is useful. Normally, this is UV or visible light emitted by flash lamps, laser diodes, or other powerful light sources. A similar pumping method can be used in gases with comparable efficiency. We talk primarily about photodissociation lasers where excited atoms or radicals are produced via broadband absorption leading to the dissociation of multi-atomic molecules. The photolytic iodine laser in Table 1 is an example wherein excited iodine atoms are produced via photodissociation of multi-atomic molecules, typically  $\text{CF}_3\text{I}$  or  $\text{C}_3\text{F}_7\text{I}$ . The difference from solids is that the gas medium allows wider creativity in designing a pump source that can be “immersed” into the active laser volume, for example, as in the successful detonation of explosives placed inside a gas filled chamber. The radiating shock wave reaches a black body temperature of  $\sim 50,000^\circ\text{K}$  generating a great deal of UV for pumping. Similar brightness can be obtained from a high-current electric discharge initiated by an “exploding wire” or in a surface discharge, as illustrated by Figure 1. Multi-kilojoule iodine lasers aimed to defense applications have been demonstrated since the 70’s using these pumping methods.

Although able to generate large amounts of energy per pulse, the repetition rate of the photolytic laser is restricted by the pump source. Below I review more conventional pulsed gas lasers available at, or above, 1 kHz and 1 kW of the average power.



**FIGURE 1:** Surface electrical discharge inside a photolytic gas laser chamber.

### 3. CONVENTIONAL HIGH-POWER GAS LASERS

#### 3.1 Types of High-Power Gas Lasers

Table 2 gives side-by-side comparison of five of the most advanced and powerful gas lasers. All produce more than 1 kW of average power at a high repetition rate. There is a broad choice of wavelength coverage from UV to mid-IR. Looking at the last row that shows the theoretical limit for the pulse duration defined by the gain bandwidth we see that only excimer and high-pressure CO<sub>2</sub> lasers show promise for generating ultrashort pulses. Other lasers do not meet this criterion because they operate on atomic- or light-molecular transitions at a relatively low pressure, thus the transform limit for pulse duration is about 0.1-1 ns. Still, they were not omitted from this review because these lasers have other merits that should not be disregarded, especially that of high wall-plug efficiency. Later, we may well find an opportunity to use them as pump sources in ultrafast laser projects.

TABLE 2. Gas lasers able to attain the high-repetition sub-nanosecond pulse regime

Parameter	Excimer discharge	Iodine chemical	HF chemical	CO discharge	CO <sub>2</sub> discharge
Wavelength [ $\mu$ m]	0.2-0.5	1.3	3	4-5	9-10
Average Power [kW]	1	10	100	10	50
Pulse Rep. Rate [kHz]	0.1-10	1	1	1	1
Wall-Plug Efficiency [%]	15	30	180	70	10
Gas Consumption	closed loop	kg/min	kg/min	closed loop	closed loop
Min. Pulse (Theory) [ps]	0.15	1000	100	100	0.15

#### 3.2 Chemical Lasers

In Section 2, I discussed the atomic iodine laser. Due to its higher efficiency and average power, another type of the same laser, the Chemical Oxygen Iodine Laser (COIL) became more strategically important in antimissile defense. Its main difference is that, instead of using a flashlight as a pump source, it uses a chemical reaction. A big advantage of chemical lasers lies in the relatively small power generator required to initiate an exothermic chemical reaction. The rest of the pump's energy is stored in the fuel. Figure 2 illustrates the principles used in the design of the COIL. A fuel (Cl<sub>2</sub> gas) is mixed with oxidizer (basic hydrogen peroxide) in a combustion chamber, a spark is ignited and a product collected - excited molecular oxygen. Next, it is mixed with an iodine vapor and flashed through a nozzle where the components interact producing excited iodine atoms. Lasing is achieved in an optical cavity set across the expansion chamber.

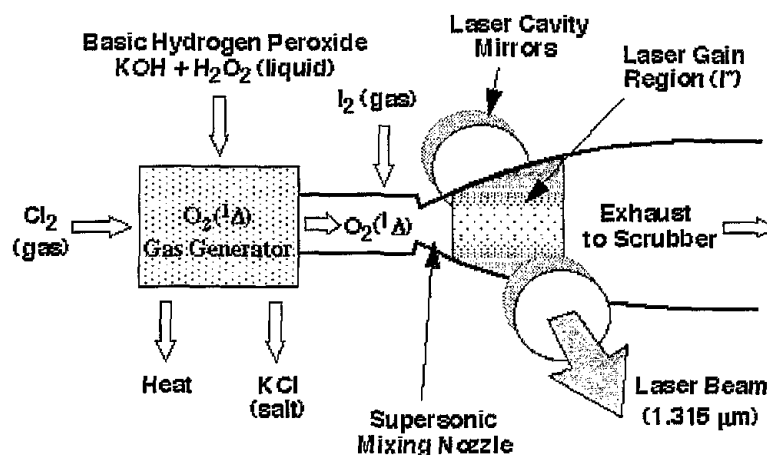


FIGURE 2. COIL - Chemical Oxygen Iodine Laser.

The iodine laser was selected for aerial applications because its 1.3  $\mu\text{m}$  wavelength falls into the atmospheric transmission window. For deployment in outer space, another type of a chemical laser weapon, the HF laser, is considered more efficient. Its design is similar to the COIL. Different types of fuel ( $\text{H}_2$  or  $\text{D}_2$ ) and oxidizer ( $\text{F}_2$ ) are mixed in a combustion chamber and hydrogen, instead of iodine, is injected into the nozzle producing vibrationally excited HF (hydrogen fluoride) or DF (deuterium fluoride) in the chain of chemical reactions



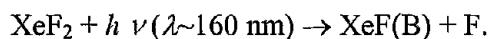
This laser operates on radiation transitions close to 3  $\mu\text{m}$  wavelength.

The present day technology of chemical lasers is at a high level; 10 kW, 1 kHz repetition rate lasers are airborne. Why not land these lasers and use them for advanced accelerators? I discuss later how such a move can be justified.

### 3.3 Excimer Lasers

Excimers are not real molecules but rather transient compositions of atoms or isomers bounded only in excited states. This is the origin of the “excimer” terminology and consequently, the reason why excimers are interesting as a laser medium. A repulsive ground state facilitates the inversion of population, the production of a high output of energy and power, and a broad spectral band necessary for amplifying short pulses. Because the excimer laser transitions originate from parent radiation transitions of relatively light atoms, they fall in the visible or UV spectral range. XeF excimer may serve an example (Figure 3).

Optical pumping is a functional option for high-power excimer lasers. We illustrate this capability with a project of a 100 TW XeF laser at the P.N. Levedev Institute [6]. The 100-nm wide bandwidth of the laser transition allows 10 fs transform-limited pulse amplification. Similar to a photolytic iodine laser, this laser is based on a broadband molecular photodissociation



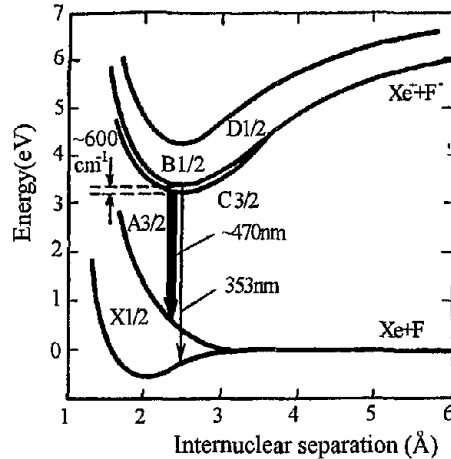
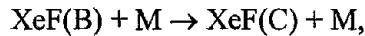
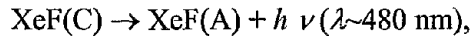


FIGURE 3. Energy levels of XeF excimer laser.

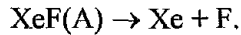
This is followed by a fast collisional relaxation to the upper laser state



laser transition



and, an immediate decomposition of the ground state



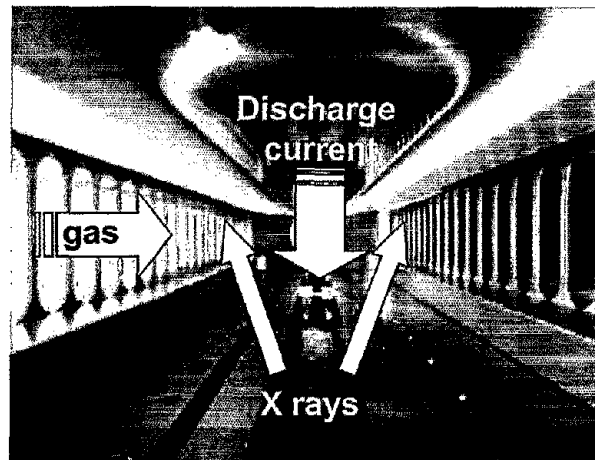
The process is energized by the UV radiation of a surface electric discharge shown in Figure 1. The laser's wavelength matches the second harmonic of a Ti:Sa laser that sends a 70 fs pulse in multiple passes through the XeF laser amplifier. A working prototype of this machine with a  $50 \times 30 \times 10 \text{ cm}^3$  slab geometry amplifies the signal forty times in 39 passes. An output of 100 TW can be obtained after 78 passes simply by doubling the scale of this machine.

Similar to a photolytic iodine laser, the XeF excimer laser can generate output pulses of above 1 kJ energy. However, such a laser is hardly scalable to a high repetition rate due to the high energy load required to produce an extended high-brightness pump source.

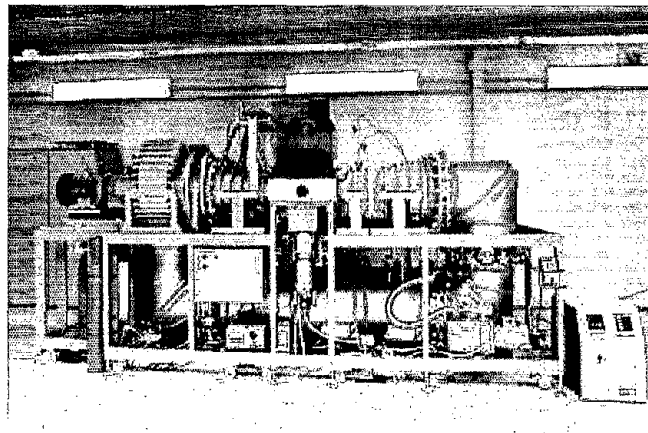
A high repetition rate regime is more achievable using transverse electric discharge excitation with the UV or x-ray pre-ionization. Figure 4 shows a typical configuration of an electrode system and a transverse gas flow inside such a laser.

VEL (very large excimer laser) manufactured by Sopra Co. (France), and shown in Figure 5, is an example of such a device. It operates on a Kr-F<sub>2</sub> gas mixture, at the output energy 10 J per pulse, 100 Hz repetition rate, and 1 kW average power. The gas components, pre-ionized by the x-ray flux and further ionized by the discharge electrons, recombine into the KrF excimer. This UV laser has a 20 THz bandwidth that allows amplification of 50 fs pulses. Note that the VEL design is typical not just for excimer lasers but can serve as a generic example of the most popular type of gas lasers pumped by volumetric electric discharge; thus it could be a CO<sub>2</sub> gas laser.





**FIGURE 4.** Inside view of a high repetition rate gas laser excited by non-self-sustaining electric discharge.



**FIGURE 5.** High repetition rate excimer laser manufactured by SOPRA Co.

### 3.4. Conventional CO<sub>2</sub> Lasers

Figure 6 explains why the CO<sub>2</sub> laser's wavelength is an order-of-magnitude longer than that of iodine or excimer lasers: the excitation is not electronic but vibrational. A three-atomic CO<sub>2</sub> molecule has three vibration modes: symmetric and asymmetric valence modes, and a deformation mode. The diagram in Figure 6 shows the low vibrational levels of the CO<sub>2</sub> and N<sub>2</sub> molecules that are involved into the laser action. The notations identify levels of excitation of the CO<sub>2</sub> vibrational modes. N<sub>2</sub> molecules, excited in the electrical discharge via nonelastic collisions with electrons, resonantly transfer energy to CO<sub>2</sub> molecules that emit radiation in two strong 9- $\mu$ m and 10- $\mu$ m vibrational bands.

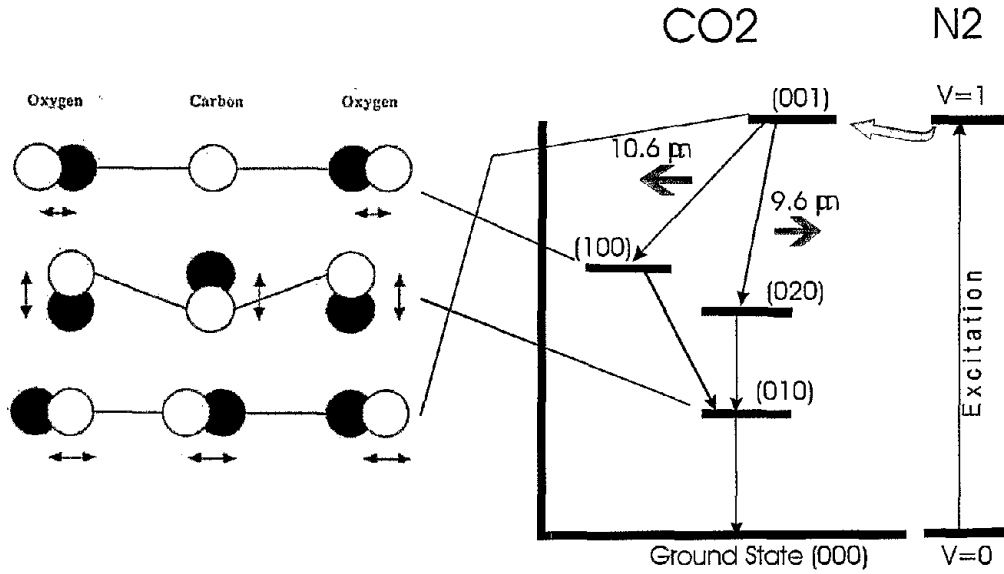


FIGURE 6. Vibrational modes and low energy levels of a CO<sub>2</sub> molecule.

The vibrational bands are composed of a sequence of spectral lines that correspond to transitions between multiple rotational sublevels (see Figure 7). Selection rules for symmetric CO<sub>2</sub> molecules allow only the transitions where the rotational quantum number changes by  $\pm 1$ . These sequences constitute correspondingly *P*- and *R*-branches of vibrational bands with the central lines defined by the following expressions:

$$\nu_P = \nu_0 + B_1 J(J+1) - B_2 (J+1)(J+2),$$

$$\nu_R = \nu_0 + B_1 J(J+1) - B_2 (J-1)J.$$

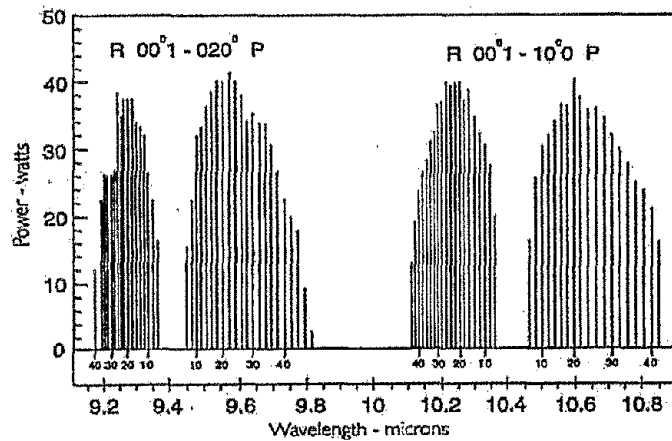


FIGURE 7. Rotational structure of the CO<sub>2</sub> radiation spectrum.

At the normal discharge temperature, the maximum line strength is at  $J \sim 20$  and the typical interline spacing varies between  $1.4 \text{ cm}^{-1}$  (38 GHz) for 9R-band to  $1.8 \text{ cm}^{-1}$  (55 GHz) for 10P-band. Each branch contains about 20-30 rotational lines and covers  $\sim 1 \text{ THz}$  bandwidth.

The strongest transition corresponds to  $\lambda = 10.6 \text{ }\mu\text{m}$ . Powerful industrial lasers operate at this wavelength at any desired repetition rate up to CW. However, conventional  $\text{CO}_2$  lasers are not suited to the ultrashort pulse regime. The problem is that these lasers operate at a low sub-atmospheric pressure. In this case, the rotational structure limits the short pulse amplification. When a picosecond pulse with the spectral envelope, shown with a smooth curve on the bottom left frame of Figure 8, propagates in a low-pressure amplifier it splits into a train of pulses (the top right frame in Figure 8). Smoothing the molecular spectrum via pressure broadening helps to minimize the laser pulse's distortions. At 10 atm pressures, a complete overlap of individual rotational lines in quasi-continuum allows amplification of a picosecond pulse.

## 4. HIGH-PRESSURE PICOSECOND $\text{CO}_2$ LASERS

### 4.1 Infrared Benefits

Several advanced accelerator schemes benefit from a long wavelength of  $\text{CO}_2$  lasers. The first attractive point is that a  $\text{CO}_2$  laser allows a viable compromise between conventional RF technology and optical laser drivers. In particular, this facilitates structure-based accelerators, production of micro-bunches and their re-phasing to the laser field, as was demonstrated in the dual-stage laser accelerator STELLA [4].

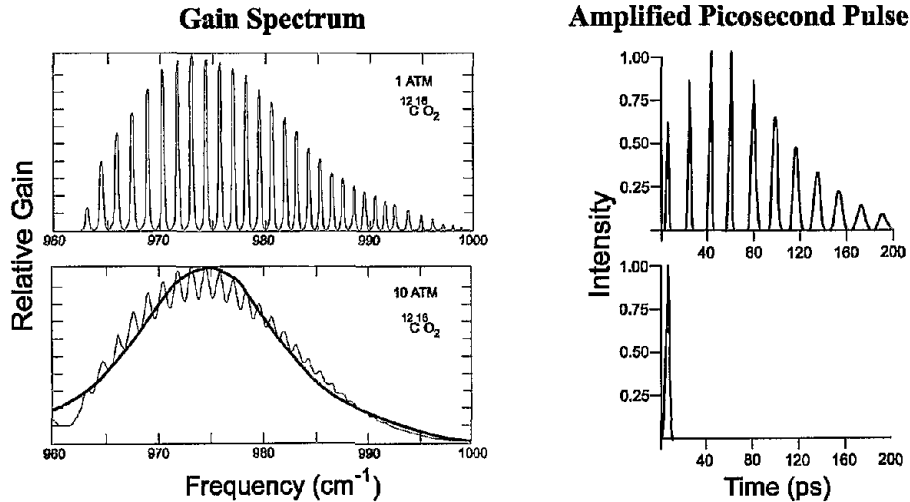


FIGURE 8. Amplification of 1 ps pulse at 1 atm and 10 atm amplifier pressure.

The degree to which physics is relativistic is determined by a ponderomotive potential – the energy acquired by an electron during the half period of oscillation in the electromagnetic wave  $W_{osc} = e^2 E^2 / 2m\omega^2 = a^2 mc^2 / 2$ . Due to the quadratic dependence of  $W_{osc}$  upon laser frequency, at a given intensity, a CO<sub>2</sub> laser reaches 100 times higher ponderomotive potential than does a solid-state laser. This implies the possibility of a proportional increase in a throughput of laser-induced processes, such as particle acceleration and x-ray production.

At first glance, these arguments can be dismissed due to tighter diffraction-limited focusing of short-wavelength beams,  $w_0 \sim \lambda$ , where  $w_0$  is the laser focus waist radius. The transverse electric field  $E_L$  associated with laser power  $P$  is defined by  $|E|^2 = 2P / \pi \epsilon_0 c w_0^2$  that seemingly cancels the dependence of  $W_{osc}$  upon  $\omega^2$ .

Let us consider, however, two practical situations where over-tight focusing is not productive:

Ensuring laser/e-beam interaction for monoenergetic acceleration or x-ray generation via Thomson scattering requires that the laser's focus is broader than the electron beam. A CO<sub>2</sub> laser has sufficient focusing capability to match the size of the low emittance electron beams.

Considering volumetric interactions, for example, high harmonic generation via an above-threshold ionization of atoms and molecules, the ten times tighter focus of the 1- $\mu\text{m}$  laser results in an equivalent specific yield from the 1000 times smaller volume  $w_0^2 \times z_0$ , where  $z_0 = \pi w_0^2 / \lambda$  is the Rayleigh distance. Thus, the integral yield is 1000 times below one of a CO<sub>2</sub> laser.

These simple considerations suggest that, in certain situations, a 1 TW CO<sub>2</sub> laser may be equivalent to the 100 TW solid-state laser. This justifies developing ultrafast CO<sub>2</sub> laser technology.

## 4.2 Generation and Amplification of Picosecond CO<sub>2</sub> Laser Pulses

Presently, only two laser facilities scale high-pressure CO<sub>2</sub> laser technology to the terawatt power level: the Neptune laboratory at UCLA, and the ATF at BNL (Figure 9).

Let us see how short CO<sub>2</sub> pulses are produced and amplified. First, a CO<sub>2</sub> laser cannot generate picosecond pulses without the assistance of a short-wavelength laser, which controls a semiconductor optical switch. The switch actually is a polished slab placed at the Brewster angle and transparent to the incident p-polarized CO<sub>2</sub> laser beam. The short-wavelength laser pulse, having photon energy above the band gap of a semiconductor, creates an electron-hole plasma in a surface layer. When the plasma reaches the critical density, of  $10^{19} \text{ cm}^{-3}$  for  $\lambda=10 \mu\text{m}$ , the refractive index becomes imaginary, and the semiconductor surface briefly turns into a metal-like mirror. Figure 10 illustrates this process. Using two sequential switches allows slicing a pulse adjustable in length. Next, a sliced seed pulse can be sent for amplification.

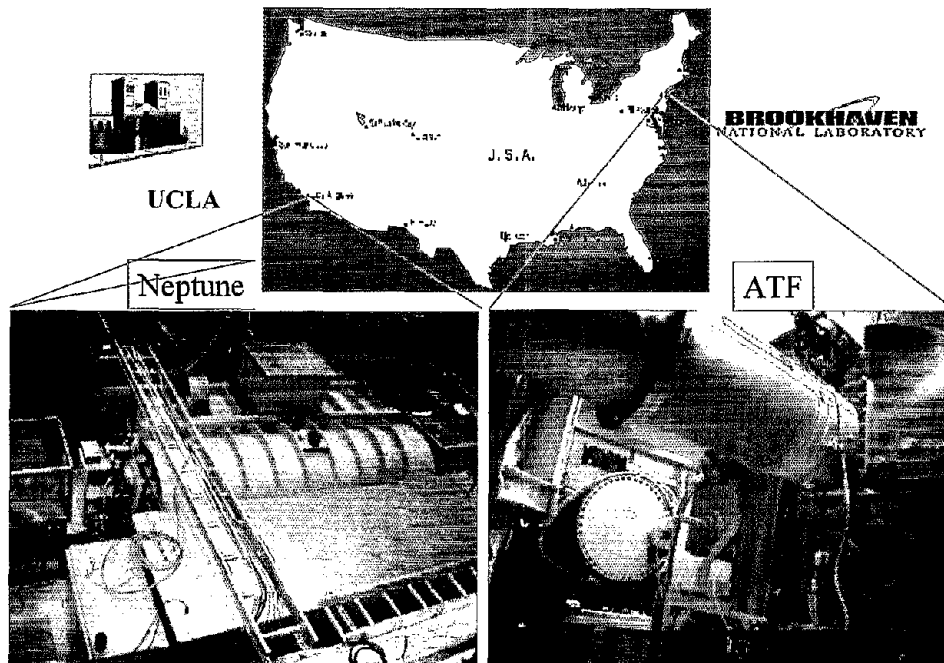


FIGURE 9. Two facilities.

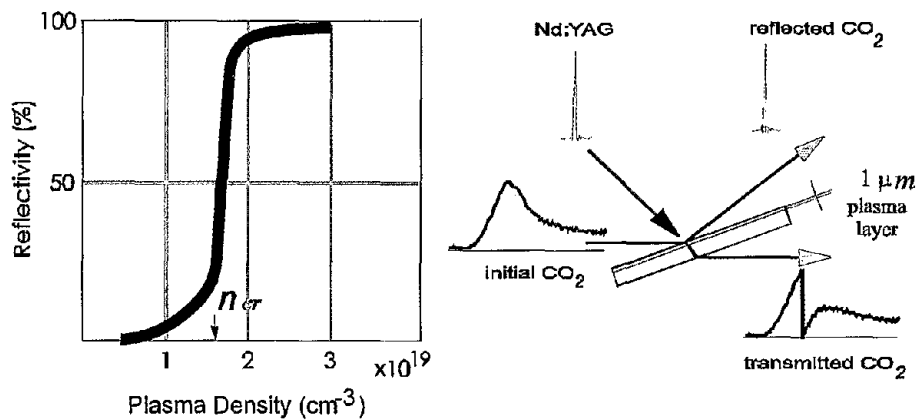


FIGURE 10. Semiconductor switching of picosecond CO<sub>2</sub> pulses.

A high-power picosecond CO<sub>2</sub> laser system is illustrated here by the example of the ATF laser. For the initial power boost from the MW to the GW level, we use a commercial 10-atm laser preamplifier manufactured by SDI Ltd. (Pretoria, S. Africa). To achieve the TW power, a custom big-volume amplifier PITER I (stands for Picosecond Terawatt) was built in St. Petersburg, Russia by Optoel Co. The development of this laser was a good opportunity to learn more about the high-pressure gas laser technology and its limitations.

A spatially uniform self-sustained glow discharge can exist only at  $Pd < 25$  torr cm. At a higher pressure, an auxiliary source of ionization is needed - UV, x-ray, or e-beam pre-ionization. However, high-pressure discharge is an unstable process, and, at 10 atm, contracts into arcs over  $\sim 300$  ns interval. This means that a high-pressure laser can be operated only in a pulsed regime.

PIITER I with the 1 m of the active length and an active volume  $V_a = 10$  l, pre-ionized with a build-in x-ray tube, and energized with a 1 MV discharge achieves a small-signal gain  $g_0 = 2.5$  %/cm.

Amplification of picosecond pulses from the initial fluence  $W_0$  measured in J/cm<sup>2</sup> is simulated by solving Maxwell-Bloch equations describing the interaction of the laser radiation with the excited CO<sub>2</sub> energy levels [7]. A computer-generated curve can be fitted by the Franz-Nodvik equation

$$W(z)/W_s = \ln\{1 + \exp(g_0 z)[\exp(W_0/W_s) - 1]\},$$

where  $W_s = 500$  mJ/cm<sup>2</sup> is the saturation fluence. The product of  $g_0 \times W_s \times V_a \approx 100$  J gives the stored energy available for extraction from the active medium in a single pass. However, the laser beam covers just a portion of the active volume and does not reach saturation. Consequently, the obtained output is at the 10 J level. The length of the output pulse is 25 ps, measured with a single-shot autocorrelator. The minimum pulse length is limited by the Nd:YAG control pulse, of 14 ps.

In principle, much shorter CO<sub>2</sub> laser pulses are possible. For example, 2 ps 0.1 TW pulses from a rather miniature amplifier were demonstrated two decades ago [8]. It is just a matter of using an appropriately short control pulse in semiconductor switches. The ATF is upgrading its equipment to produce multi-terawatt pulses 2-3 ps long.

### 4.3 Prospects: Femtosecond Pulses

Finally, I consider the prospects for large-scale ultrafast CO<sub>2</sub> technology. Can this be pushed to the limit of a few cycles? Note that the semiconductor switching speed is limited just to the length of the control pulse. For example, Corkum achieved 130 fs (4 cycles) CO<sub>2</sub> pulses sliced with a 70 fs dye laser [9].

There are possibilities for directly amplifying such a pulse. The most straightforward way is to build a really broad 7 THz continuum in the CO<sub>2</sub> amplifier gain spectrum by mixing all possible isotopes of oxygen and carbon [10].

Another possibility is to convert the energy of a nanosecond CO<sub>2</sub> pump pulse into the frequency-downshifted short seed pulse via Raman scattering in the resonance plasma [11]. Raman scattering does not just add to the intensity of the short pulse but also compresses it. Simulations for the 1 ns 5 J pump pulse at  $\lambda = 9$   $\mu$ m and a 10 ps seed pulse at  $\lambda = 10$   $\mu$ m counter-propagating in the  $n_e = 10^{17}$  cm<sup>-3</sup> resonance plasma show that the signal pulse shrinks down to a single cycle, that is 33 fs for 10  $\mu$ m radiation, and acquires multi-terawatt power.

Another approach for pulse shortening based on frequency chirp due to gas ionization was practically implemented for the first time at the Neptune laboratory. The UCLA Mars amplifier operates at 3 atm pressure that sets a 200 ps minimum to the transform-limited pulse. Transmitting a focused laser pulse through a gas cell changes the

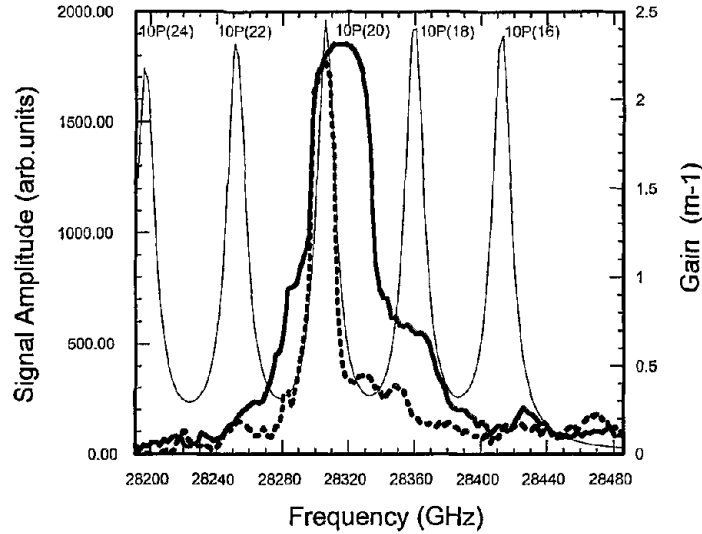
refraction index due to ionization  $n(x,t) = \sqrt{1 - n_e(x,t)/n_{cr}}$  with the subsequent frequency chirp along the laser pulse

$$\Delta\omega = \frac{\pi n_e^0}{\lambda n_{cr}} \frac{\partial}{\partial t} \int n_e(x,t) dx.$$

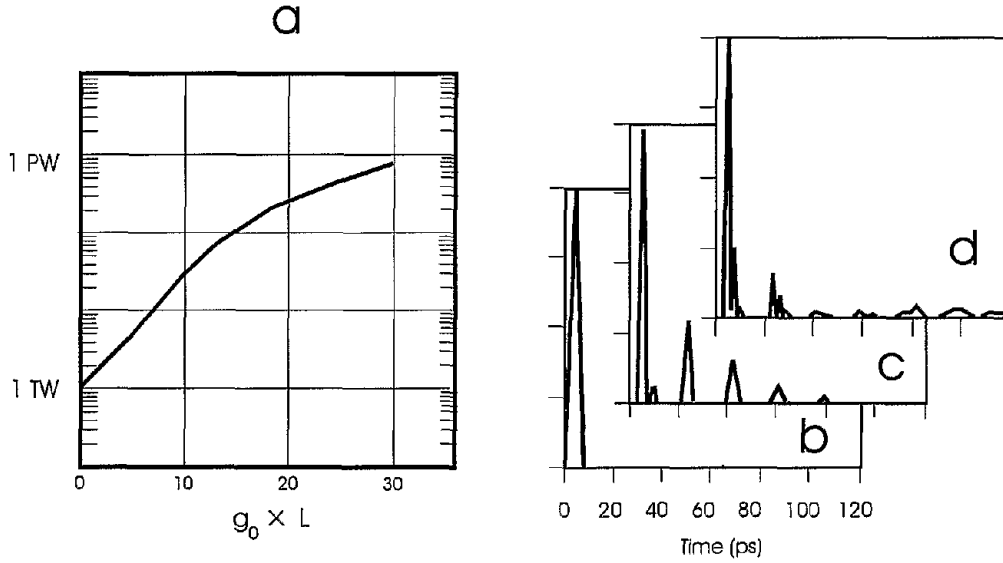
When the pulse is returned back into the amplifier, the chirped tail is filtered out by the gain as is shown in Figure 11. This way, the output pulse is compressed from 200 ps to 40 ps [12]. Corkum earlier suggested using a similar chirping in a gas with a succeeding negative dispersion material ( $d\eta/d\omega < 0$ ) for compressing the initially 1-2 ps pulses down to 150-100 fs.

#### 4.4 Prospects: Petawatt Power

UCLA researchers observed also the effect of power- or Stark-broadening  $\Delta\nu_s = \mu E/\hbar$  ( $\approx 37$  GHz @  $I=10^{10}$  W/cm<sup>2</sup>) that, similar to the pressure-broadening, builds a bridge between rotational lines to provide sufficient bandwidth for the 1 ps pulse amplification [12]. Simulations show that if a 1 TW picosecond pulse is seeded into the Mars amplifier, close to 1 PW can be extracted after four passes with a beam expansion to the 30 cm aperture (Figure 12). Thus, it is just a matter of modifying the front end of the Neptune laser system to produce a proper seed pulse. The ATF laser may serve here as an example of such a system.



**FIGURE 11.** CO<sub>2</sub> laser pulse spectrum with a chirp (solid line) and after filtering (dashed line) overlaid over the amplifier gain spectrum.



**FIGURE 12.** Simulations of the 3-ps CO<sub>2</sub> pulse amplification in the Mars amplifier; a) power gain with the 30 times beam area expansion, b) 10 MW initial pulse, c) 1 TW pulse after PITER I at the entrance to the Mars amplifier, d) 1 PW pulse after the Mars amplifier.

#### 4.5 Prospects: High Repetition Rate

Limitations to the repetition rate of the high-pressure lasers are primarily technical due to the required high energy loading of  $\sim 100$  J/atm into the medium. PITER I and Mars CO<sub>2</sub> lasers are not designed for operation at a high repetition rate. The 30-second interval between the pulses delivered by PITER I is determined by the low power of the DC power supply. The repetition rate might be improved by straightforwardly upgrading the DC power supply, building a pulse-forming network on semiconductor high-voltage switches, quickly circulating gas through a catalytic converter, and using a faster vacuum pump for the x-ray tube. Still, 1-10 Hz is about the limit that can be achieved with a high-pressure laser pumped with electric discharge. How then can we make a high-power picosecond CO<sub>2</sub> laser system operate at a higher repetition rate?

Several choices look promising. They include chemical pumping and optical pumping, which also split to several options. Most of the applicable optical pumping schemes are based on using a nanosecond low-pressure laser that can operate at  $\sim 1$  kHz rate, and on transferring energy to a picosecond pulse. First, let us recall the Raman backscattering method mentioned in the previous Section.

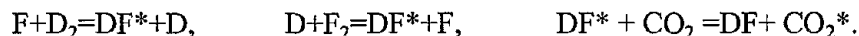
In other scheme, a CO<sub>2</sub> laser operating at the  $9 \mu\text{m}$  band can directly pump the upper level of the  $10 \mu\text{m}$  CO<sub>2</sub> transition. However, such pumping requires preheating of the gas that does not confer high efficiency.

It is well known that CO<sub>2</sub> lasers can pump very efficiently several other molecular gases, thus obtaining lasing in the mid- and far-IR region. One example is NH<sub>3</sub>. A tube could be filled with NH<sub>3</sub> gas, then pumped by the energetic 10 ns CO<sub>2</sub> laser pulse, sending shortly afterwards a 10 ps signal at a downshifted frequency. To obtain a high gain, a cryogenic temperature is required. The spectrum of NH<sub>3</sub> does not allow the amplification of pulses shorter than 10 ps [13].



Finally, I review a scheme that has a particularly high potential for progressing to a high pulse energy and repetition rate. The same chemical energy that is released by burning hydrogen in fluorine and results in lasing on the HF molecule can be optically transferred to a mixture of the CO<sub>2</sub> and NO<sub>2</sub> molecules (see Figure 13) [14]. This process is close to 100% in pumping quantum efficiency and can be carried out at the high pressure necessary for picosecond pulse amplification. The abundance of the deposited energy per liter of the laser volume gives a relatively high gain of 10%/cm, permitting the use of a more compact amplifier than the one pumped with the electric discharge.

Another possibility that is worth exploring is pure chemical pumping via direct energy transfer from DF\* to CO<sub>2</sub> in reactions

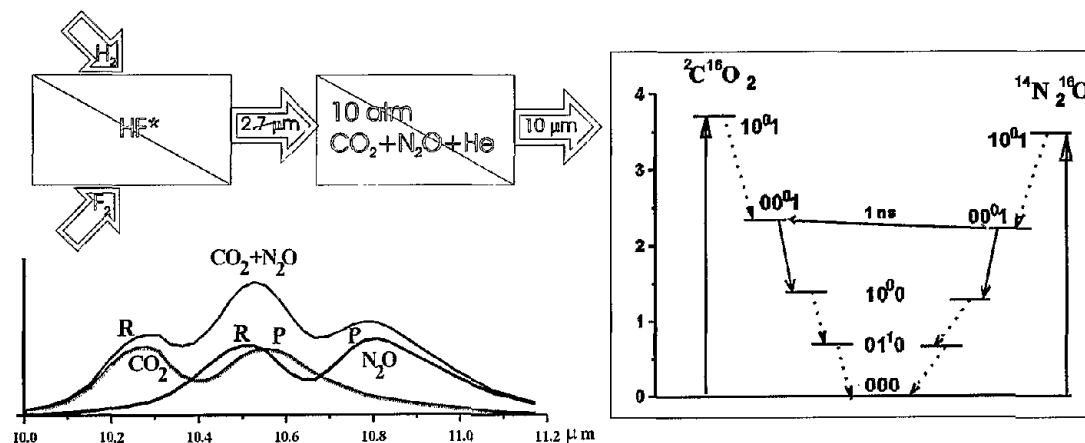


## 5. CONCLUSIONS

From this brief review of the high-power pulsed lasers and analysis of their applicability to laser accelerators and other strong-field projects, I highlight the following observations and conclusions:

Gas laser technology has a potential to meet the needs of the advanced high-energy physics applications that may require picosecond or femtosecond pulses, more than 1 TW peak power, up to 1 kHz repetition rate, and 1 kW or higher average power. As the closest fit to these requirements, the CO<sub>2</sub> laser also has a fundamental advantage due to the  $\lambda^2$  scaling of the ponderomotive potential.

A hypothetical 1 PW  $\lambda=10 \mu\text{m}$  laser focused to the diffraction limit with a realistic  $\#F=1$  will produce a field with  $a=70$  and might efficiently realize several highly relativistic processes, such as a high-flux GeV ion injector, direct ponderomotive acceleration of electrons in the laser focus, and studies of Unruh radiation.



**FIGURE 13.** Luminescence spectra and low vibrational levels of the CO<sub>2</sub>-N<sub>2</sub>O gas mixture.

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