Gas Lasers
for strong field applications

tutorial

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MOTIVATION

- Why are we talking today about gas lasers? Indeed, 99% of publications on advance acceleration or broader high power laser scientific applications consider solid state lasers.

- Meantime CO$_2$ gas lasers enabled:
  - the first laser beatwave acceleration
  - ICA and IFEL electron acceleration
  - the first and only staged and monoenergetic laser accelerator
  - the strongest Thomson scattering source

- All above with just two gas laser facilities operating for this kind of experiments

- Developing practical alternative solutions for particle accelerators and radiation sources requires taking all the best from both solid state and gas laser technologies and pushing these technologies up in power, rep. rate, etc.
OUTLINE

- GAS LASERS:
  - spectral range from UV to Far-IR
  - kW and even MW of average power
  - wall plug efficiency up to 70%

- Active medium:
  - atoms, molecules, excimers

- Variety of pumping schemes:
  - electric discharge, electron beams,
    optical and chemical pumping
We narrow our scope to gas lasers capable to produce pico- and femtosecond pulses with relativistically strong normalized fields $a > 1$ and high repetition rate.

We will review several ongoing projects in this field.

Special attention is given to picosecond $CO_2$ lasers that proved to be a valuable tool for strong-field physics applications.

Finally, we will analyze possibilities for generating $CO_2$ laser pulses of the Petawatt peak power and a few cycles long.
## Typical Parameters of Solid State and CO$_2$ Lasers

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Solid State</th>
<th>10-atm CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host matrix density (cm$^{-3}$)</td>
<td>$10^{23}$</td>
<td>$10^{20}$</td>
</tr>
<tr>
<td>Active particle density (cm$^{-3}$)</td>
<td>$10^{20}$</td>
<td>$10^{19}$</td>
</tr>
<tr>
<td>Photon energy (eV)</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Stored energy (J/cm$^3$)</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>Gain (%/cm)</td>
<td>~50</td>
<td>3-4</td>
</tr>
<tr>
<td>Active volume (cm$^3$)</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>Output energy (J)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Bandwidth (THz)</td>
<td>5-50</td>
<td>1</td>
</tr>
<tr>
<td>Average power (kW)</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
Lasers with Optical Pumping

Solid State Laser

Photodissociation Iodine Laser

$\lambda \sim 1 \, \mu m$
Lasers with Optical Pumping

Solid State Laser

\[ \lambda \sim 1 \, \mu m \]

Photodissociation Iodine Laser

\[ \lambda = 1.3 \, \mu m \]
COIL - Chemical Oxygen Iodine Laser

Basic Hydrogen Peroxide
KOH + H2O2 (liquid)

Cl2 (gas)

O2(1Δ)
Gas Generator

Heat
KCl (salt)

I2 (gas)

O2(1Δ)

Laser Cavity Mirrors

Laser Gain Region (1")

Exhaust to Scrubber

Supersonic Mixing Nozzle

Laser Beam (1.315 μm)
Chemical laser

- An HF chemical laser uses F as the oxidizer and H2 as the fuel
- A COIL device uses excited O2 as the oxidizer and I2 as the fuel
Chemical laser

\[ H_2 + F_2 = H + HF + F \]
\[ H_2 + F = HF^* + H \]

\[ HF^* \rightarrow \lambda = 2.7 \mu m \]
\[ DF^* \rightarrow \lambda = 3.6 \mu m \]
COIL in flight
(chemical oxygen iodine laser) (cartoon)
Gas lasers capable to high average power and repetition rate

<table>
<thead>
<tr>
<th></th>
<th>Excimer, discharge or photopump</th>
<th>Iodine, photo-chemical</th>
<th>HF, chemical</th>
<th>CO₂ (CO), discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [µm]</td>
<td>0.2-0.3</td>
<td>1.3</td>
<td>3-4</td>
<td>9-10 (4-5)</td>
</tr>
<tr>
<td>Average Power [kW]</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Repetition Rate [kHz]</td>
<td>0.1-10</td>
<td>10</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Wall-Plug Efficiency [%]</td>
<td>15</td>
<td>30</td>
<td>180</td>
<td>30 (70)</td>
</tr>
<tr>
<td>Gas Consumption</td>
<td>closed loop</td>
<td>kg/min</td>
<td>kg/min</td>
<td>closed loop</td>
</tr>
<tr>
<td>Min. Pulse (Theory) [ps]</td>
<td>0.03</td>
<td>1000</td>
<td>100</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Photochemical XeF excimer laser

\[ \text{XeF}_2 + h\nu (\lambda \approx 160 \text{ nm}) \rightarrow \text{XeF}(B) + F \]
\[ \text{XeF}(B) + M \rightarrow \text{XeF}(C) + M \]
\[ \text{XeF}(C) \rightarrow \text{XeF}(A) + h\nu (\lambda \approx 480 \text{ nm}) \]
\[ \text{XeF}(A) \rightarrow \text{Xe} + F \]

\text{Bandwidth 100 nm \Rightarrow}
\text{Transform limited pulse duration 10 fsec}

\text{Up to 1 kJ energy demonstrated}

\text{Wavelength match to frequency doubled Ti:Sa}

\text{Courtesy of D. Mikheev}
\text{P.N.Lebedev Physical Institute}
\text{Quantum Radiophysics Division}
\text{Photochemical Processes Laboratory}
Photochemical XeF amplifier of fsec optical pulses

Multi-channel surface discharge active medium size $3 \times 11 \times 50 \text{ cm}^3$

Courtesy of D. Mikheev
P.N.Lebedev Physical Institute
Quantum Radiophysics Division
Photochemical Processes Laboratory
100 TW project

Achieved amplification x40 in 39 passes

Required: $1.6 \times 10^3$ in 78 passes

Contrast $10^{10}$

Courtesy of D. Mikheev
P.N. Lebedev Physical Institute
Quantum Radiophysics Division
Photochemical Processes Laboratory
Electrical discharge excimer laser

10 J per pulse, 100 Hz repetition rate, 1 kW average power

gas flow
Example of multi-stage high repetition rate excimer laser

Demonstrated:
10 ps,
400 Hz x 20 pulse/train = 8 kHz rep. rate,
50 W average power

Possibility:
1 kW with SOPRA-class laser amplifier
Bandwidth 20 THz allows 50 fs amplified without stretching

KrF laser

\[ \text{KrF}^* \rightarrow \text{harpooning} \]

KrF* + F

Kr+ + F- \rightarrow \text{KrF}^*
Benefits of using long-wavelength ($\lambda=10\mu$m) CO$_2$ laser:

• Combines advantages of high-quality conventional RF accelerators and high-gradient optical accelerators with $\lambda = \sim 1 \mu$m
  • favorable phasing
  • structure scaling.

Illustrated by STELLA - the first two-stage laser accelerator

• Ponderomotive potential that controls x-ray production, plasma wake generation and other strong-field phenomena is proportional to $\lambda^2$.

Illustrated by Thompson scattering experiment – presently the brightest Thomson x-ray source.
...but $\lambda=1 \, \mu\text{m}$ permits tighter focusing (assuming $w_0 \sim \lambda$)!

However:

- **Interacting with e-beam** you do not want to focus laser tighter than e-beam (decreases acceleration quality and x-ray yield). CO$_2$ laser focusing is sufficient to interact with low-emittance e-beams.

- **In volumetric interactions** ten times tighter focus of the 1 $\mu$m laser results in 1000 times smaller interaction volume where we can see an equivalent effect. This will proportionally reduce the process yield.

- Thus, 1 TW CO$_2$ laser in certain cases is equivalent to 100 TW solid state laser.
**CO₂ Laser**

- CO₂ vibrational modes
- Discharge excites N₂; N₂ excites CO₂
- Radiation transitions between vibrational levels
Rotational $\text{CO}_2$ Laser Lines

- Vibrational bands are composed of transitions between rotational sublevels.
- Selection rules for symmetric $\text{CO}_2$ molecules allow only transitions where the rotational quantum number $J$ changes by $\pm 1$.
- They constitute correspondingly $P$- and the $R$-branches of vibrational bands with the central lines defined by expressions:

\[
\nu_P = \nu_0 + B_1 J (J + 1) - B_2 (J + 1)(J + 2)
\]

\[
\nu_R = \nu_0 + B_1 J (J + 1) - B_2 (J - 1)J
\]

At the normal discharge temperature the maximum line strength is at $J \approx 20$ 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.
Industrial CO$_2$ Lasers

$CW-MHz\text{- kHz-Hz}$

$>10\ kW$
Bandwidth limited amplification of ps CO₂ laser pulses

Gain Spectrum

Amplified Picosecond Pulse

Strongly modulated rotational line structure of the CO₂ gain spectrum modifies the frequency content of picosecond pulses, changing their temporal structure.

At 10 atmospheres, collisional broadening produces overlap of the rotational lines into the 1 THz wide quasi-continuous gain spectrum, and pulses as short as 1 ps can be amplified without distortion.

- Interline spacing: 40 GHz
- Pressure broadening: 5 MHz/torr
- Total bandwidth: 1 THz
- Saturation intensity $I_s = \frac{h\nu}{2\sigma\tau_R} = 3\text{ kW/cm}^2$
- Small signal gain $g_0 = \sigma N^* = 0.5\%/\text{cm}$
- Specific power available for extraction $g_0 \times I_s = 30\text{ W/cm}^2$
CO$_2$ Laser Facilities for Strong-Field Physics

UCLA

Neptune

ATF
Principle of Semiconductor Optical Switching

Plasma Density (cm$^{-3}$)

Reflectivity (%)
High-pressure ATF laser amplifier PITER I

Amplifier cell opened for maintenance

\[ P_d > 25 \text{ torr cm} \] requires ionization source (x-ray tube)

Discharge unstable after \( \tau[\mu s] \approx 3/P[\text{atm}] \) which is \( \approx 300 \text{ ns} \) at 10 atm

Energy load 120 J/l atm

Optical gain 2%/cm
25 ps CO\textsubscript{2} laser pulse measurements

The results obtained with the 25 ps optical delay gate applied to the double-staged semiconductor optical switch prior to amplification

Output beam profile

Output energy

10 J

Autocorrelator measurements

Left - intensity distribution in 10 um fundamental beams across the nonlinear crystal with a real time scale

Right - 2\textsuperscript{nd} harmonic signal corresponding to a single-shot autocorrelation function profile
Paul Corkum (NRC) demonstrated in 1986:

sliced 130 fs CO2 pulses
2 ps CO2 pulses
amplified to 0.1 TW

Generation of 130-fsec midinfrared pulses

Claude H. Holland and P. B. Corkum
Some prospects for multi-Terawatt femtosecond CO₂ pulses

Direct amplification in a 4-atm CO₂ amplifier containing a mixture of molecular isotopes with $^{12}C$, $^{13}C$, $^{14}C$, $^{16}O$, $^{18}O$. Gain bandwidth 7 THz sufficient for 150 fs pulse amplification.

Raman backscattering of 9.6 µm nanosecond pump into counter-propagating femtosecond 10.6 µm seed pulse in resonance plasma $\omega_p=\Delta\omega$. Possibility of high repetition rate as well.

Proposed by P. Corkum, V. Gordienko

Proposed by G. Shvets
Pulse Chirping and Compression in Laser Amplifier

Laser-induced ionization shifts the phase of the wave resulting in a chirp and subsequent pulse compression

\[ \eta(x,t) = \sqrt{1 - n_e(x,t)/n_{cr}} \]

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

Measured blue shift 40 GHz corresponds to \( n_e = 3 \times 10^{17} \text{cm}^{-3} \)

Can be used to compress 1 ps to 100 fs
Hypothetical combination of PITER with MARS provides 0.8 PW capability @ 1 ps

Use power or Stark broadening in laser field

\[ \Delta \nu_R = \frac{\mu E}{\hbar} \], at \(10^{10} \text{ W/cm}^2\) \[\Delta \nu_R = 37 \text{GHz}\]
Prospects for high repetition rate picosecond CO$_2$ pulses

- X-ray preionized high-pressure gas discharge controlled by semiconductor switches
- Chemical pumping via energy transfer from DF to CO$_2$
- Optical pumping or energy transfer from nanosecond CO$_2$ pulses to picosecond laser pulses
  - 9 µm CO$_2$ laser pumping of 10 µm CO$_2$ transitions
  - CO$_2$ laser pumping of other molecular gases (NH$_3$)
  - Energy exchange between counter-propagating CO$_2$ laser pulses in plasma (G. Shvets)

Predicted: 60 dB gain at 3 J/cm$^2$, 10 ns pump CO$_2$ pulse

High-pressure CO$_2$:N$_2$O laser optically pumped by HF chemical laser

Demonstrated: Pumping Efficiency 20%, SSG 10%/cm

Another possibility is direct energy transfer via reactions:
F+$D_2$=$DF^*+D$, $D+F_2$=$DF^*+F$, $DF^* + CO_2$=$DF + CO_2^*$

Courtesy of M. Azarov
Russian Academy of Science
CONCLUSIONS

- Gas lasers potentially meet the requirements for advanced strong field applications (accelerators, radiation sources).

- Molecular and excimer gas lasers can operate in a parameter range for such applications including:
  - multi-TW peak power
  - ps or fs pulse length
  - ~kHz rep rate
  - ~kW or higher average power

- The closest fit to the aforementioned requirements CO\textsubscript{2} laser has also a fundamental attraction due to the \( \lambda^2 \) proportional ponderomotive potential.

- 1 PW CO\textsubscript{2} laser scheme is feasible within the present day technology capabilities. Focused to the diffraction limit with \#F= 1, 1 PW produces field with \( a = 70 \) (do not forget \( \lambda \)-proportional spot size too !) that allows realization of highly relativistic processes such as GeV ion acceleration, ponderomotive acceleration of electrons in a laser focus, study of Unruch radiation, etc.