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Gas Laser Technology for Future Laser Synchrotron Sources

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FUTURE LIGHT SOURCES
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SCOPE

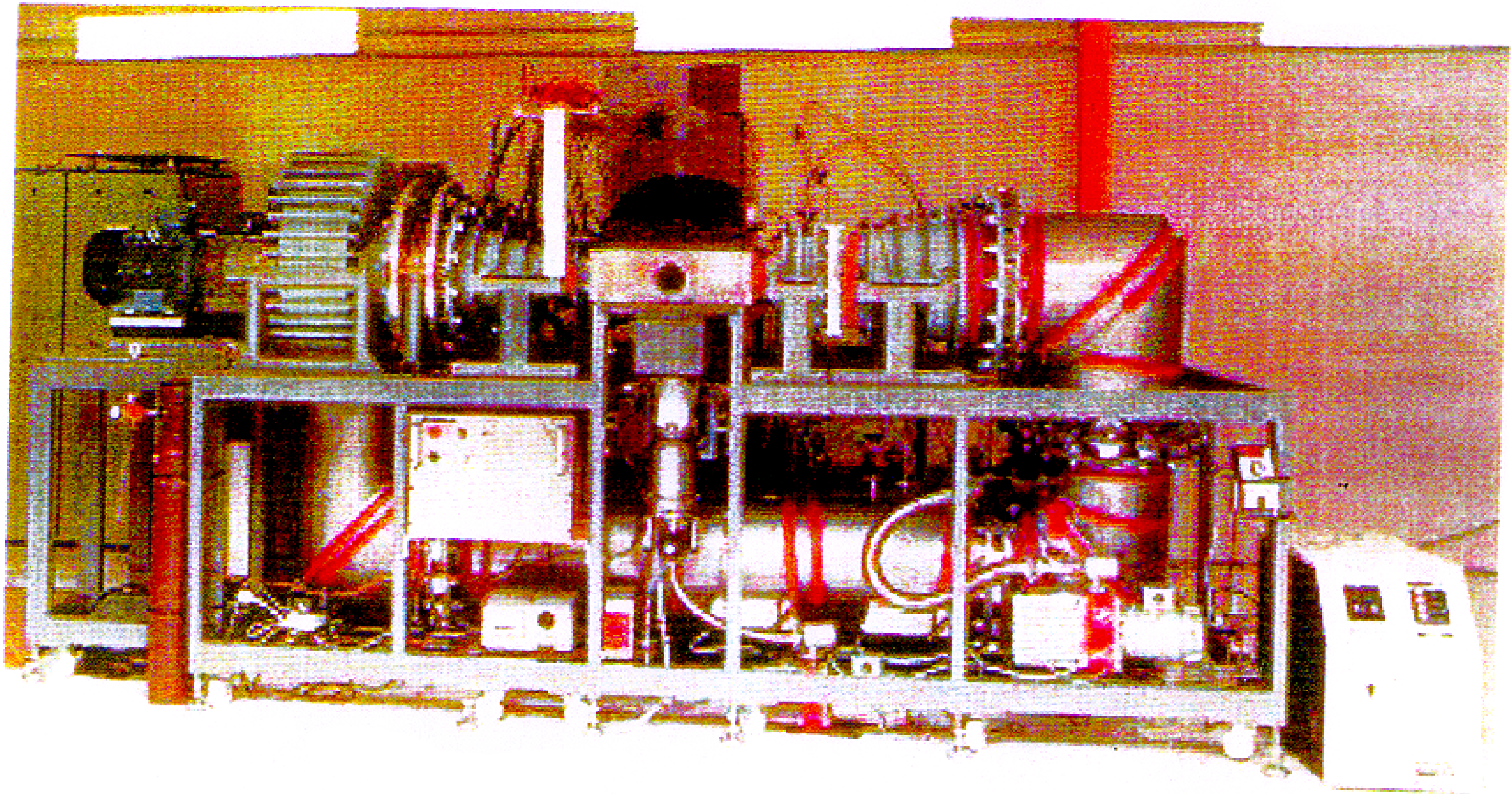
- LSS and laser accelerators will require pulsed, high peak power lasers operating at a high repetition rate compatible with the electron accelerator (around kHz)
- High yield requirements call for average power of the order of kW.
- The interacting electron and laser beams need to be tightly focused. The short Rayleigh length limits the duration of the laser pulse to a few picoseconds or less. Same for laser accelerators.
- Nanosecond laser pulses may be also useful
  - There are possibilities to transfer nano-pulses into pico-pulses.
  - For LSS we can confine the electron-laser interaction within a channel. Advantages over free space interaction: (a) avoid harmonics, (b) x-ray bandwidth is no more limited by the number of laser wavelengths within the pulse, (c) easy time synchronization.
- We search for gas lasers of pico-and nano-second pulse duration with a repetition rate in the kHz range and average power in the kW range

OUTLINE

- ◊ Review of the high repetition rate high average power gas laser technology including: molecular, excimer, and chemical lasers
- ◊ Gas lasers capability to short pulse and high peak power
- ◊ Choice of CO_2 laser based on technical efficiency and ponderomotive effect
- ◊ TW ps regime for CO_2 lasers, example - ATF laser
- ◊ Examples of TW ps CO_2 laser application:
  - ◊ laser synchrotron source
  - ◊ laser wake field accelerator
- ◊ Technical approaches to TW ps CO_2 lasers of several kW average power and high repetition rate

VEL - "Very Large Excimer Laser"

100 Hz, 1 kW, 10 J/pulse, 10 ns



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Gas lasers capable to high repetition rate in nanosecond pulse regime

	KrF, ArF, XeCl excimer discharge	Iodine photo-chemical	HF chemical	CO_2 (CO) discharge
Wavelength [μm]	0.2-0.3	1.3	3-4	9-10 (4-5)
Average Power [kW]	1	10	1	50
Pulse Repetition Rate [kHz]	0.1-10	10	0.1	1
Wall-Plug Efficiency [%]	2	>100	180	30
Min. Pulse (theory) [ps]	0.15	1000	100	0.15

KrF Laser

e^-

$F_2 : Kr : Ar$

$F_2 \rightarrow F^-$; $Kr \rightarrow Kr^+$, Kr^*

$Kr^* + F_2 \rightarrow KrF^* + F$

"harpooning"

$Kr^+ + F^- \rightarrow KrF^*$

Recombination

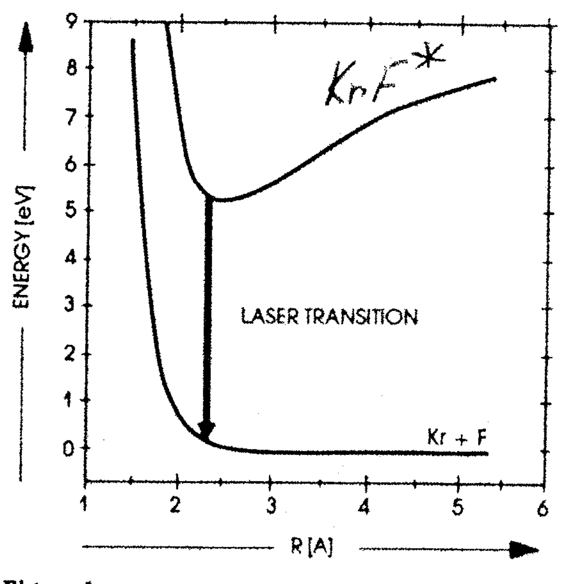


Figure 1.
Simplified potential transition curves for the KrF laser.

bandwidth
5 nm or 20 THz

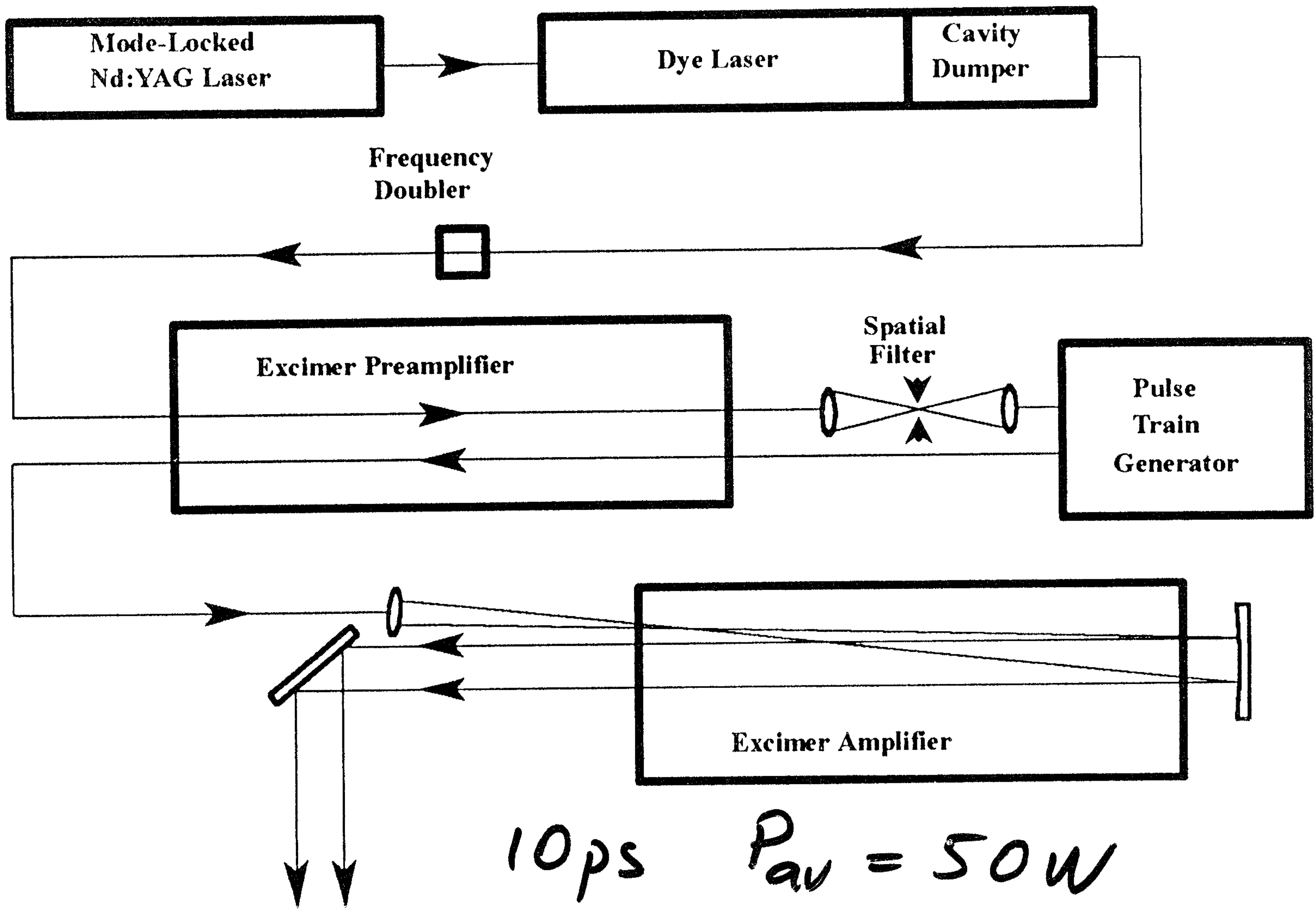
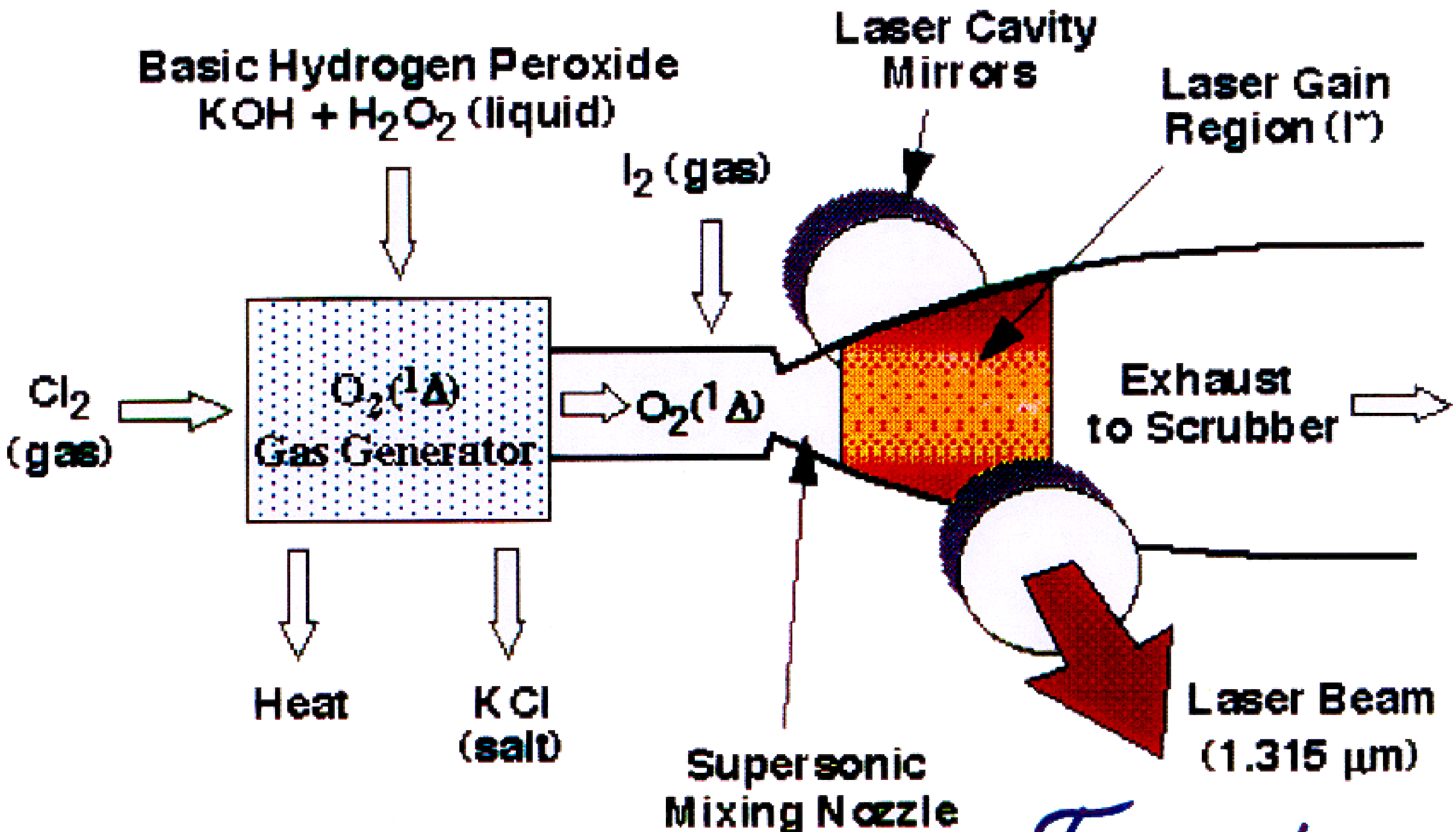


Figure 1. Laser System Schematic

$20 \frac{\text{pulses}}{\text{train}} \times 400\,Hz = 8\,kHz$

Chemical iodine laser (1.35 μm)
1 kHz 10 kW

COIL - Chemical Oxygen Iodine Laser



$\tau_{min} = 1\,ns$

Mobile 50 kW 100 Hz Russian CO_2 Laser

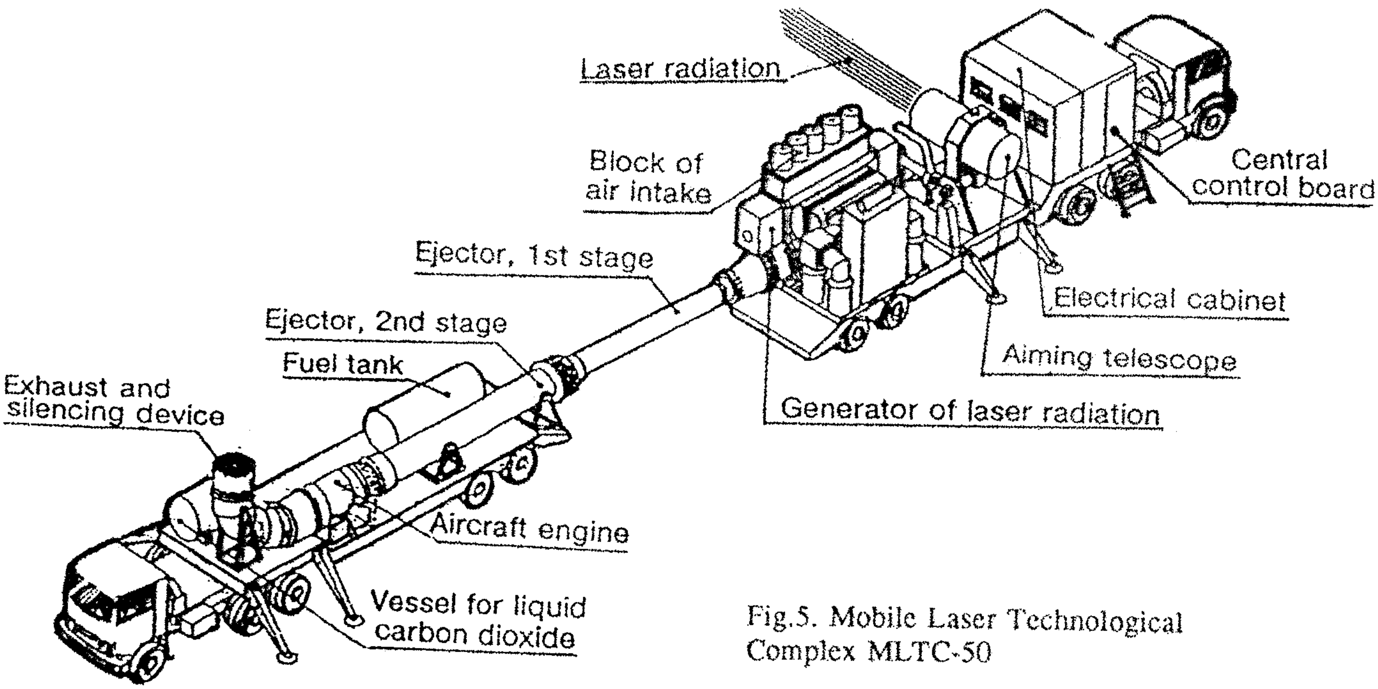


Fig.5. Mobile Laser Technological Complex MLTC-50

Type of system	HRR CO_2 laser
Laser output	50 kW
Beam divergence	≤ 0,8 mrad
Work gas consumption	
atmospheric air	4,65 kg/sec
CO_2 gas	0,35 kg/sec
Fuel outlay (kerosine TS-1)	45 kg/min
Continual work time during 1 run	1 ÷ 10 min
Interval between runs	≤ 30 min
Tracking error	≤ 0,05 mrad
Focusing range	20 ÷ 80 m
Mass	30 t
Transport means	
traction car MAZ-6422	2 piece
couple CM MAZ-93853	2 piece
Service personnel	3 persons
Power supply	≥ 600 kW
Cooling water consumption	250 l/min

For processes based on electron oscillation

(plasma wake generation or Compton scattering)

CO_2 laser permits:

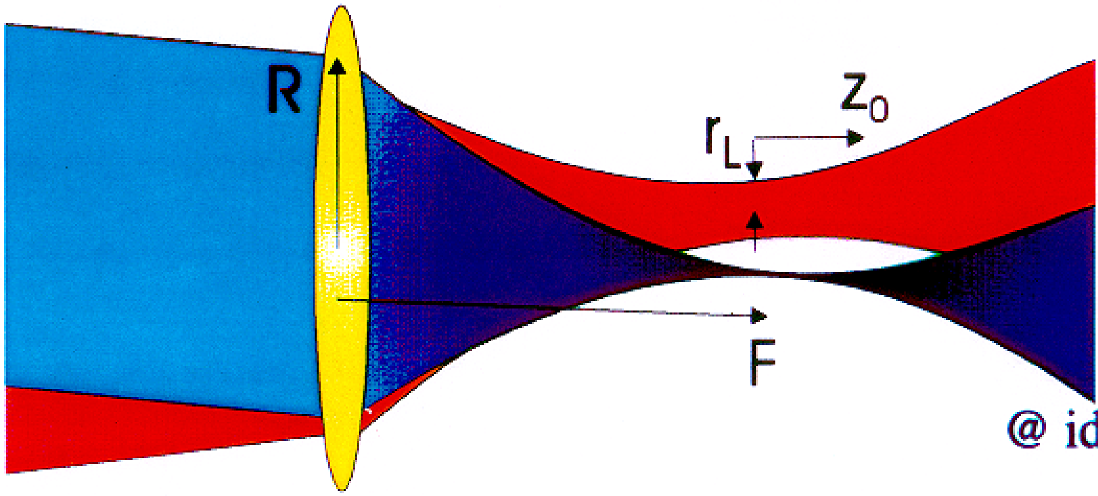
- increase (100 times to compare with λ=1 μm) in the ponderomotive potential of electron oscillatory motion $\varepsilon_p = e^2 E_L^2 / 2m\omega^2$

  characteristic for: plasma wave excitation,
  relativistic self-focusing,
  gas ionization,
  Compton scattering.

- increase (10 times to compare with λ=1 μm) in the dimensionless laser strength parameter $a = eE_L / mc\omega$

  characteristic for: laser wakefield and beatwave accelerators,
  harmonic generation.

Short wavelength permits tighter focusing...



$$r_L \approx \frac{F\lambda}{R} \quad E_L \Downarrow \lambda \Uparrow$$

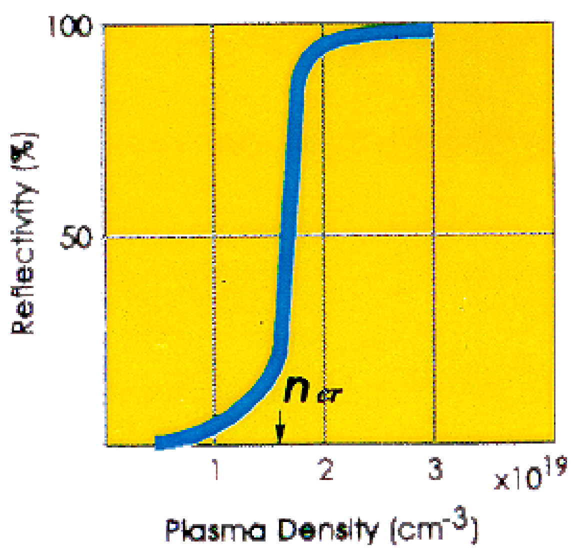
thus, $$\frac{E_L}{\omega} = Const$$

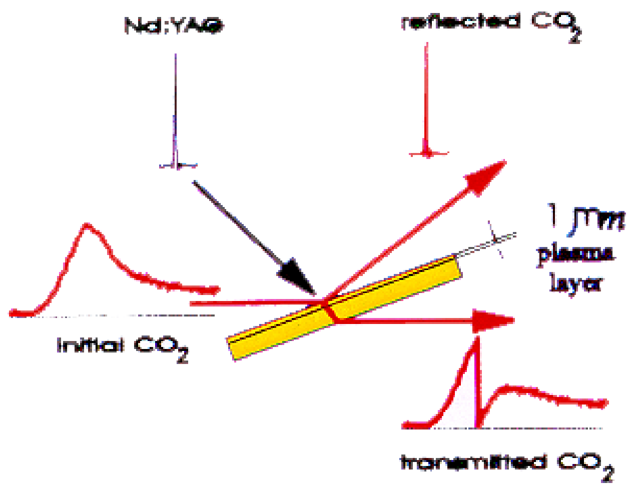
@ identical conditions (P_L, F, R)

Note, that the high-field volume $V \propto z_0 r_L^2 \propto \lambda^3$

That may define the integral number of observed events

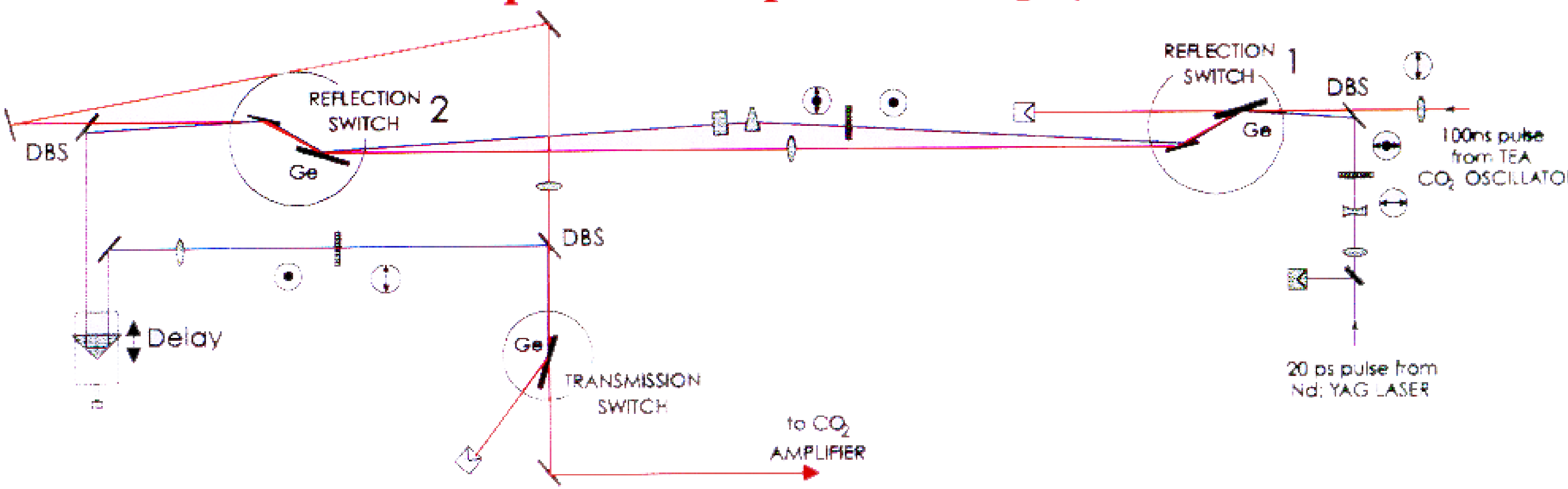
Semiconductor Optical Switching of CO_2 Laser Pulses



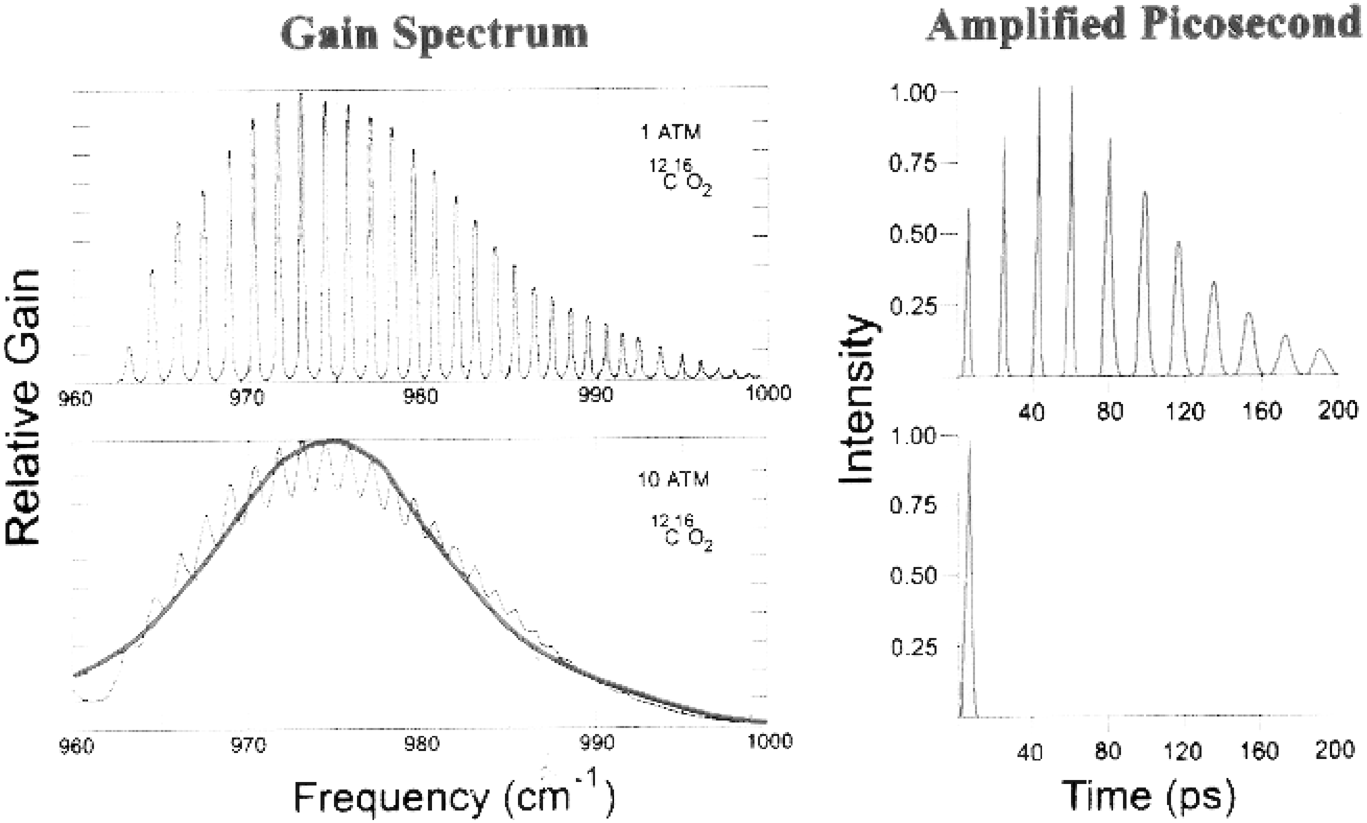


- Upon absorption of photons above the band gap energy, the semiconductor switches from transparent for λ=10 μm window to metal-like mirror.

ATF picosecond pulse slicing system

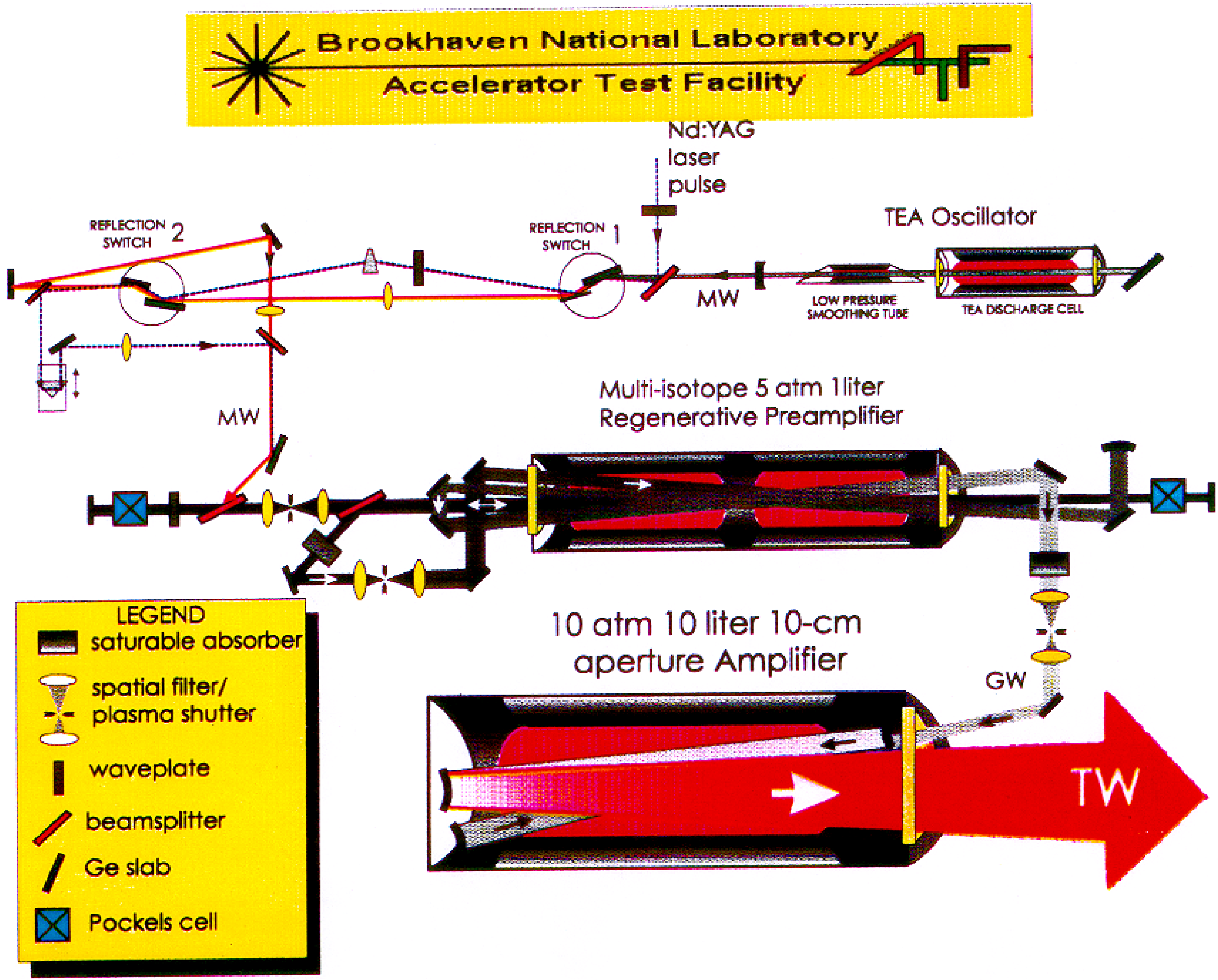


Bandwidth Limited Amplification of Picosecond CO_2 Laser Pulses



Strongly modulated rotational line structure of the CO_2 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.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Accelerator Test Facility
ATF
Nd:YAG
laser
pulse
TEA Oscillator
REFLECTION
SWITCH 2
REFLECTION
SWITCH 1
MW
LOW PRESSURE
SMOOTHING TUBE
TEA DISCHARGE CELL
MW
Multi-isotope 5 atm 1liter
Regenerative Preamplifier
10 atm 10 liter 10-cm
aperture Amplifier
GW
TW
LEGEND
saturable absorber
spatial filter/
plasma shutter
waveplate
beamsplitter
Ge slab
Pockels cell

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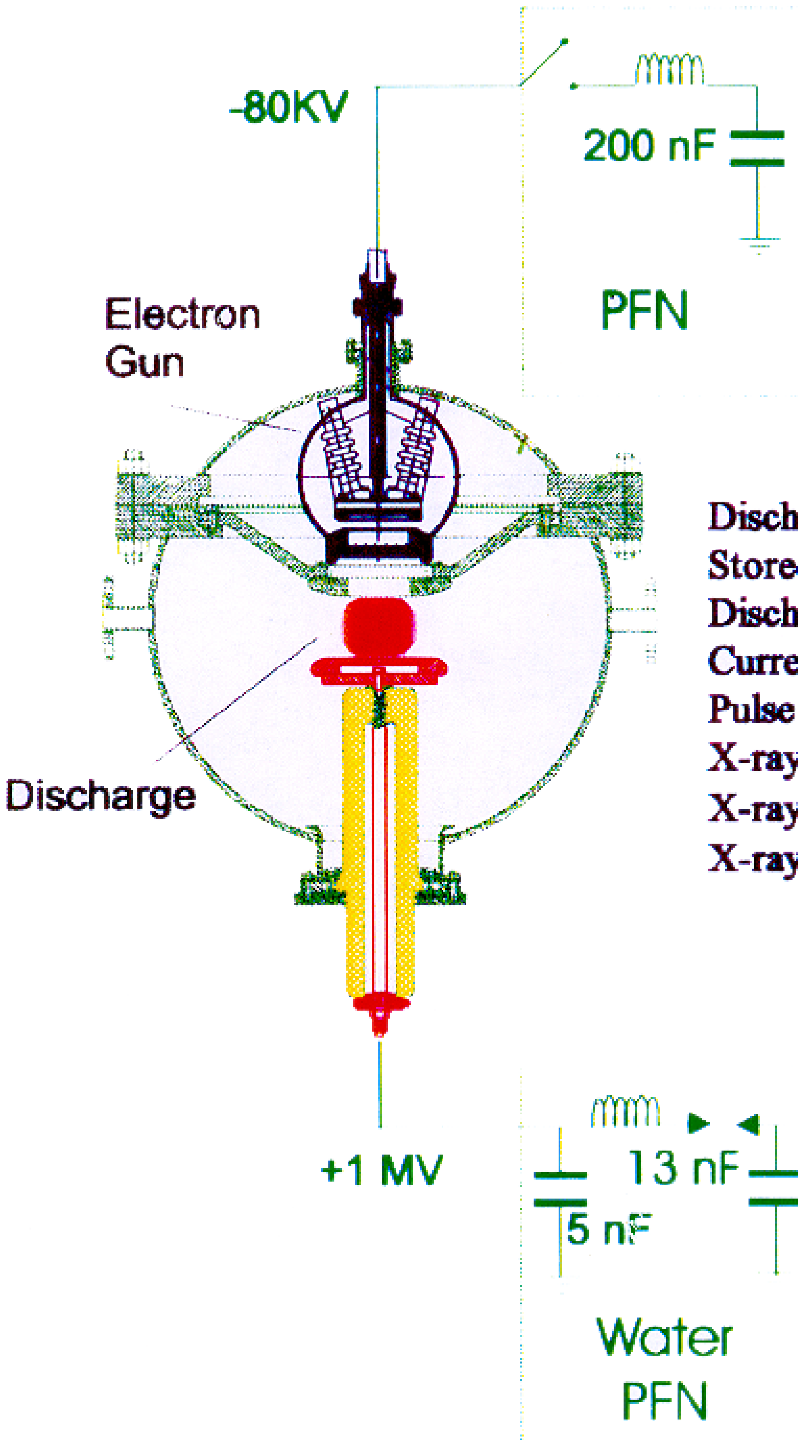
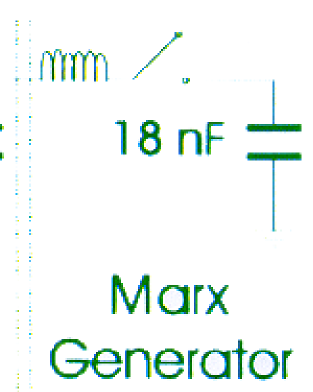
Amplifier Discharge Cell





Discharge Voltage		1 MV
Stored Electric Energy		5 kJ
Discharge peak Current		90 kA
Current Pulse FWHM		500 ns
Pulse Front		200 ns
X-ray Pulse length		2 μs
X-ray - Main Discharge Delay		1.5 μs
X-ray Dose:	at foil	0.5 R
	at ground mesh	0.1 R
	at anode	0.05 R

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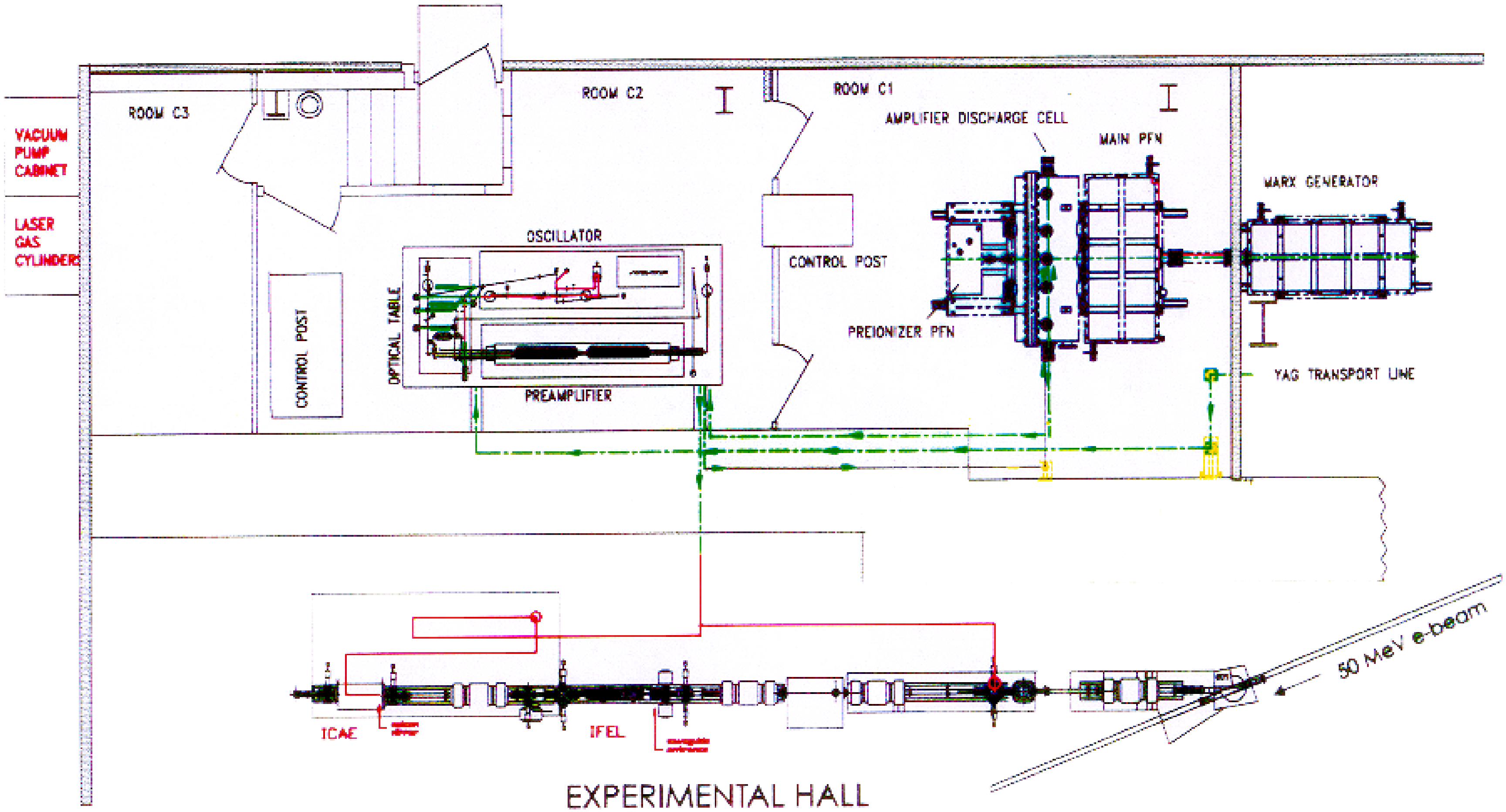
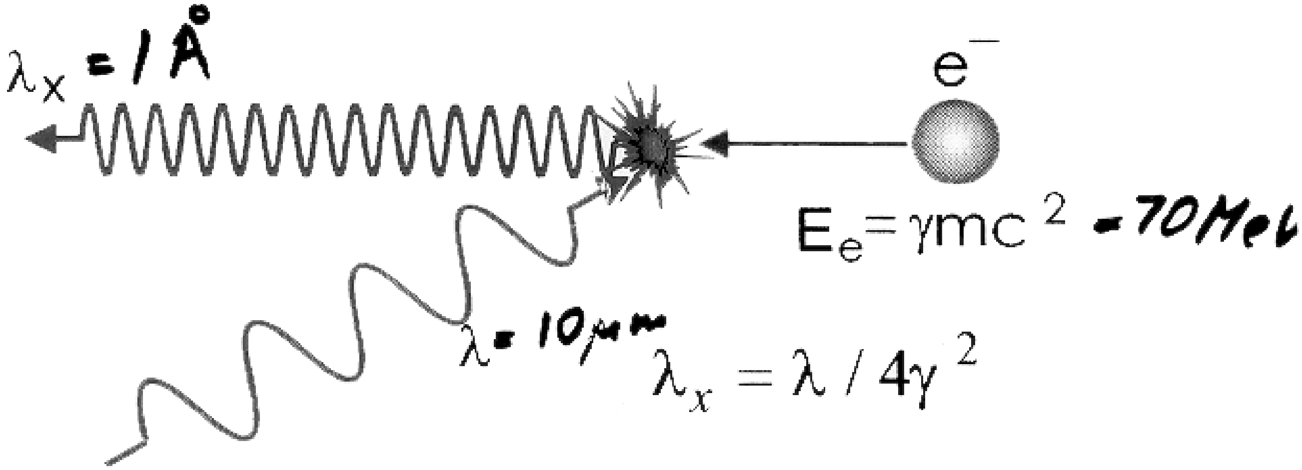
Floor plan of the BNL ATF

shows experimental hall and CO_2 laser rooms



Laser Synchrotron Source with TWps-CO_2 Driver



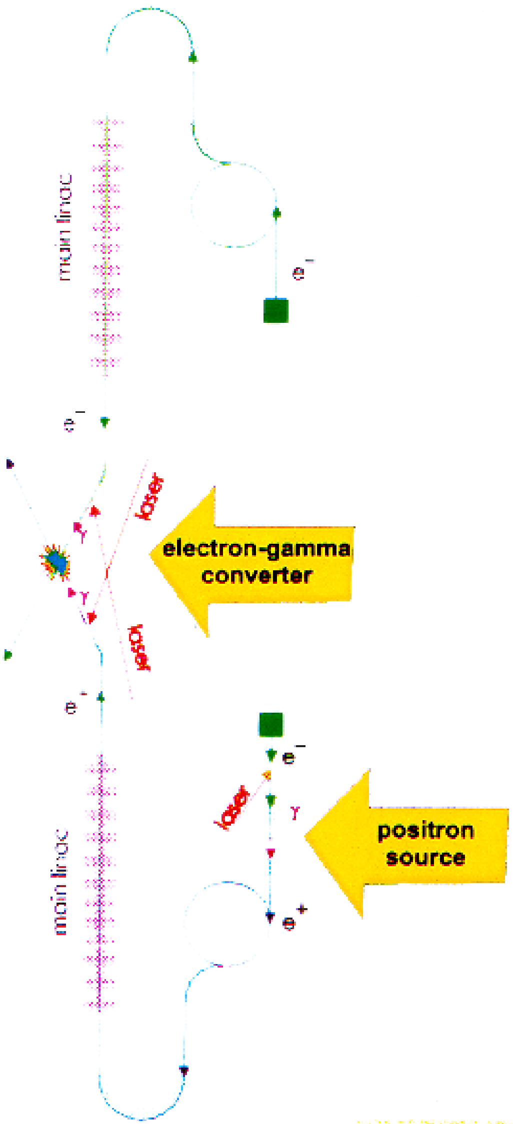
Concept of LSS permits:

- easy access to x-ray and gamma regions with compact linac
- femtosecond x-ray pulses due to available technique of ultra-short electron bunches from photocathode guns

Choosing CO_2 laser instead of 1-μm laser requires 3 times in γ increase, then:

- Divergence $\theta \approx 1/\gamma$ drops 3 times
- Flux $P_x \propto \lambda E_L Q\gamma^2/\tau_b r_b^2$ increases 10 times
- Brightness $B \propto P_x/(2\pi r\theta)^2$ increases 100 times

Electron⇒Gamma Converters for Future Linear Colliders



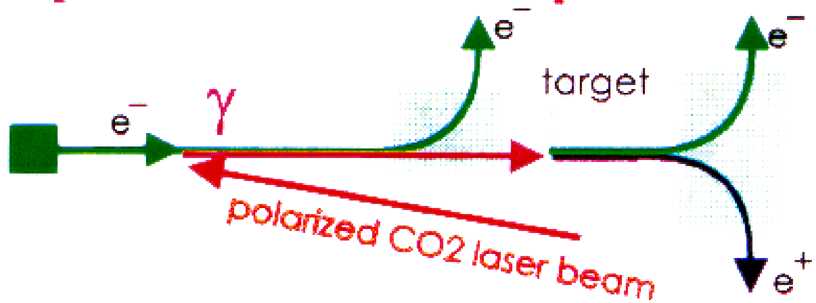
CO_2 laser for $e^- \Rightarrow \gamma$ converter at 2.5 TeV

- $\hbar\omega_\gamma = \left[x/(x+1)\right]E_e$, where $x = 4E_e\hbar\omega/m^2c^4$

  For E_e=2.5 TeV and λ=10 μm, x=4.8 and $\hbar\omega_\gamma \approx E_e$
- Rescattering $\gamma+\lambda \Rightarrow e^- + e^+$ when $\omega\omega_\gamma > m^2c^4/\hbar^2$ or λ[μm]<4.2E_e[TeV].

  For the E_e=2.5 TeV, λ=10.5 μm is the optimum choice.
- For τ_L=1 ps, probability of the $e^\pm \Rightarrow \gamma$ conversion $\chi = \sigma_c \mathbf{E}_L/\hbar\,\tau_L c^2$ reaches unity at the laser pulse energy $E_L \approx 1$ J.
- Fast-flow TWps-CO_2 laser operating at 100 Hz repetition rate will amplify trains of a hundred 1 ps pulses spaced by 1 ns (aggregated pulse repetition rate 10 kHz) at wall-plug efficiency 10%.

Polarized positron source for Japan Linear Collider



CO_2 laser produces 10 times more photons per joule than solid state laser

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TMU

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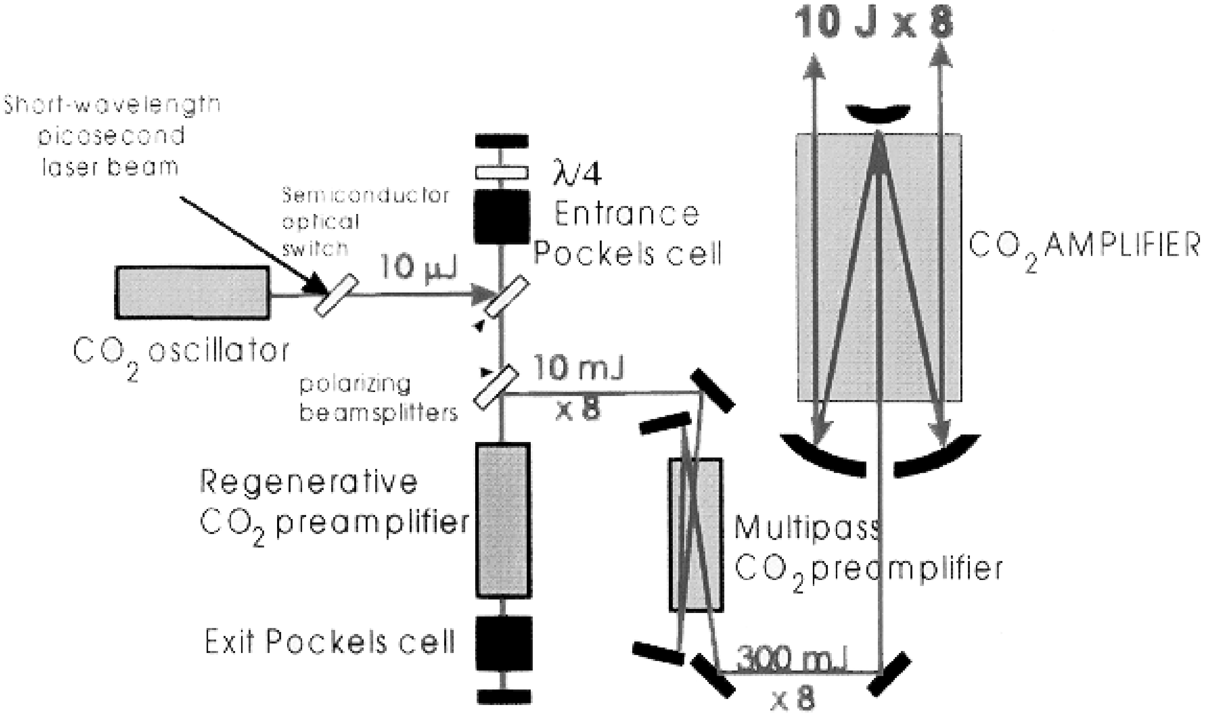
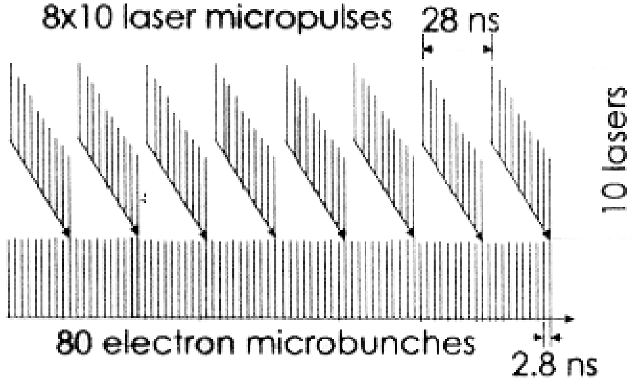
Pulse-Train Picosecond CO_2 Laser



Example of pulse train laser multiplexing to fit requirements of the JLC polarized positron source



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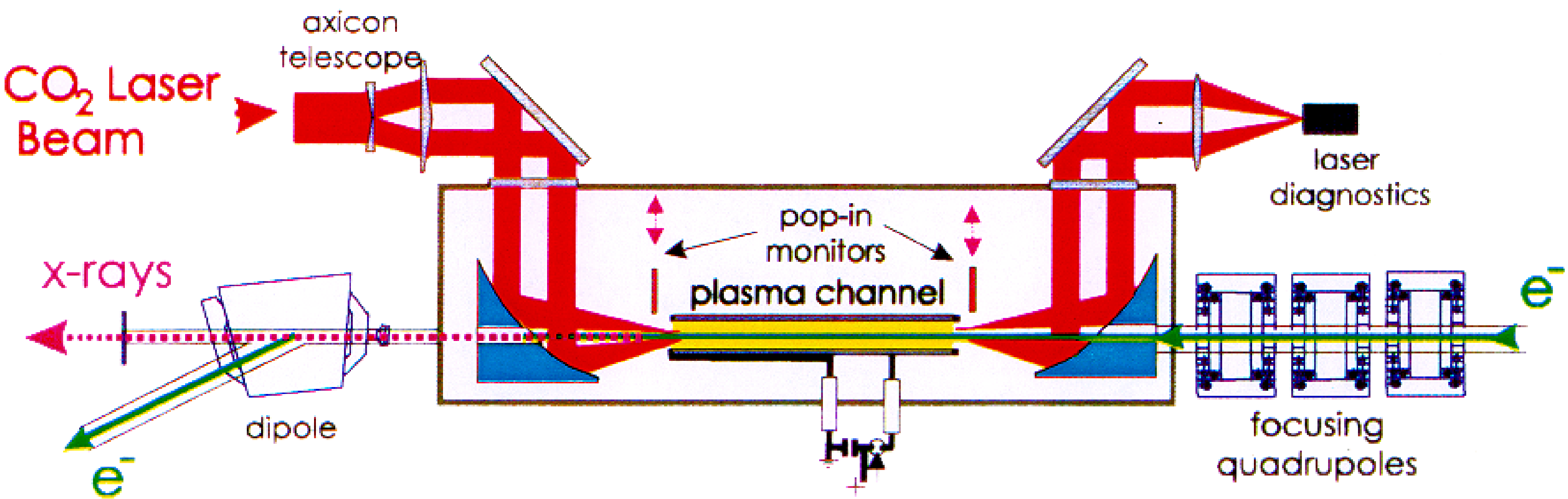
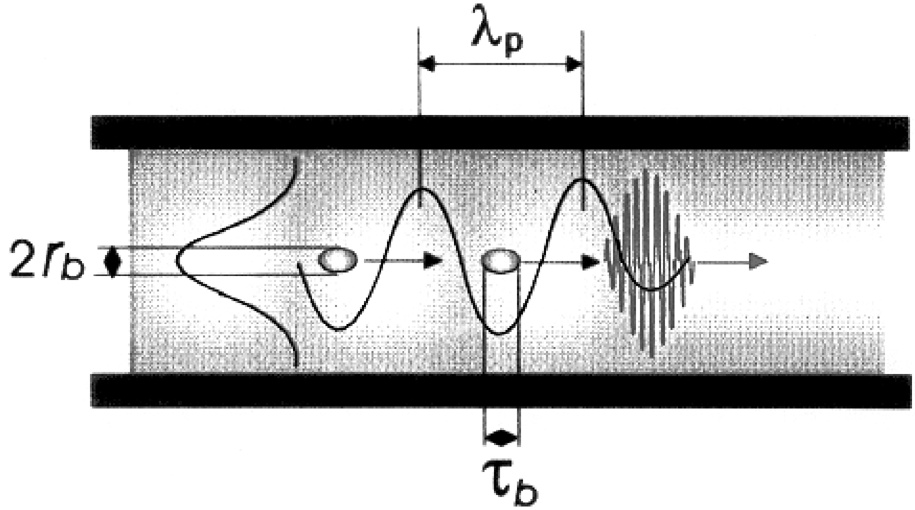
Prospective Compton Scattering Experiment in Plasma Channel



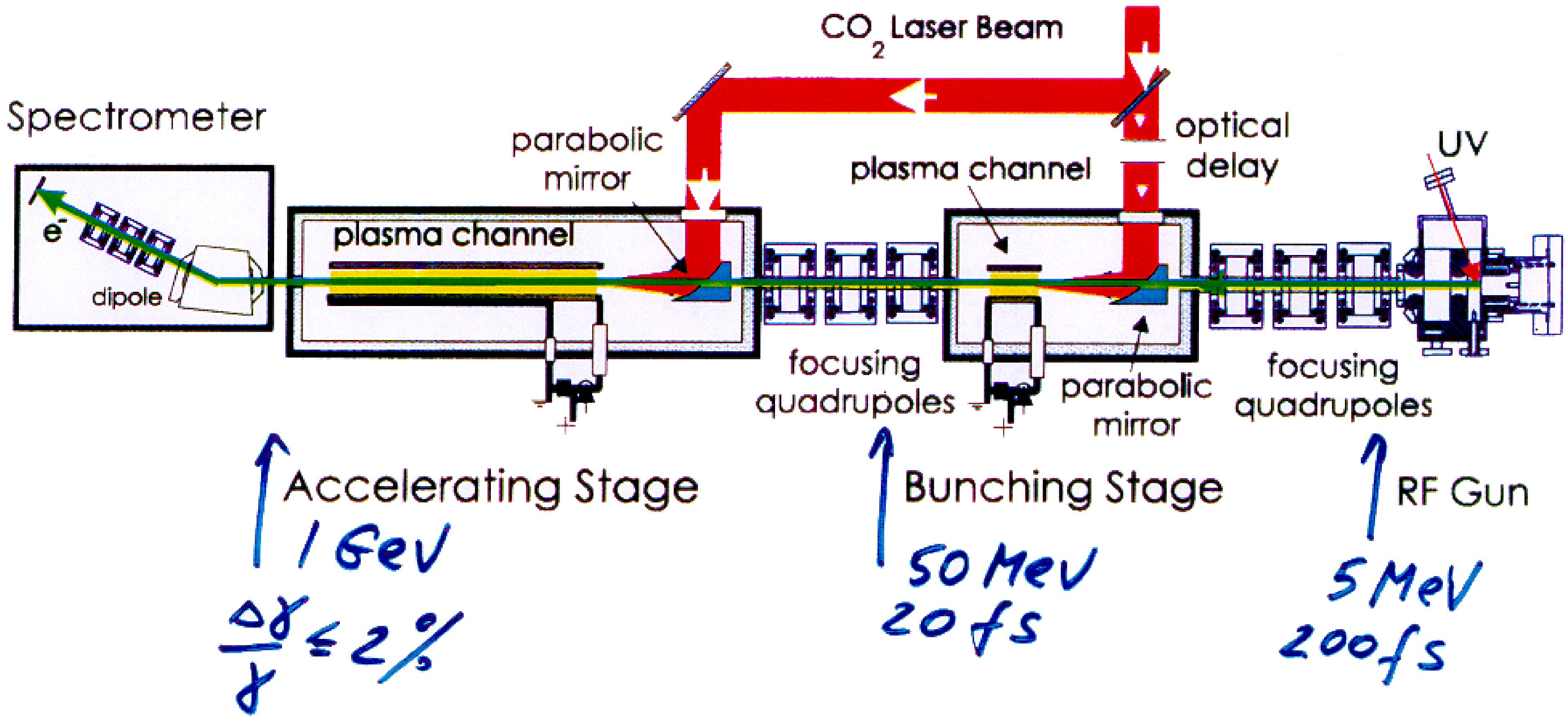
Approach to monochromatic LWFA

- **Linear regime of plasma wakefield generation (a<1)**
- **Channeling of the laser beam**
- **Longitudinal and transverse sizes of the injected electron bunch have to be small to compare with λ_p**



- **Maximum bunch charge** $N_e^{\max} \propto \lambda_p$
- **The maximum amplitude of the accelerating plasma wakefield** $E_a^{\max}[\mathrm{GV/m}] = 2.8\times10^4\left(\frac{\lambda}{r_L}\right)^2 P_L[\mathrm{TW}]/\lambda_p[\mu m]$
- Combination of terawatt picosecond CO_2 laser with subpicosecond photocathode electron gun - opens the way to practical monochronatic laser accelerators

Principle diagram of the two-stage monochromatic LWFA



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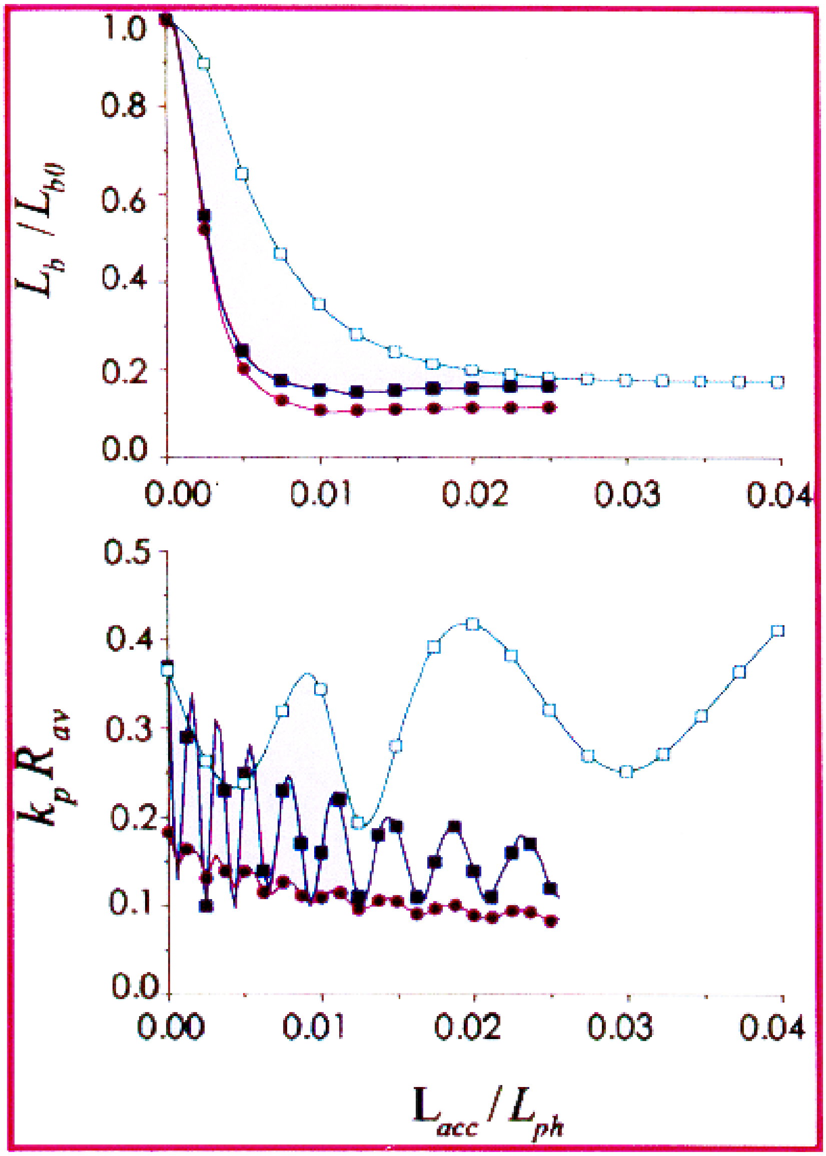
Bunch compression in channel guided LWFA



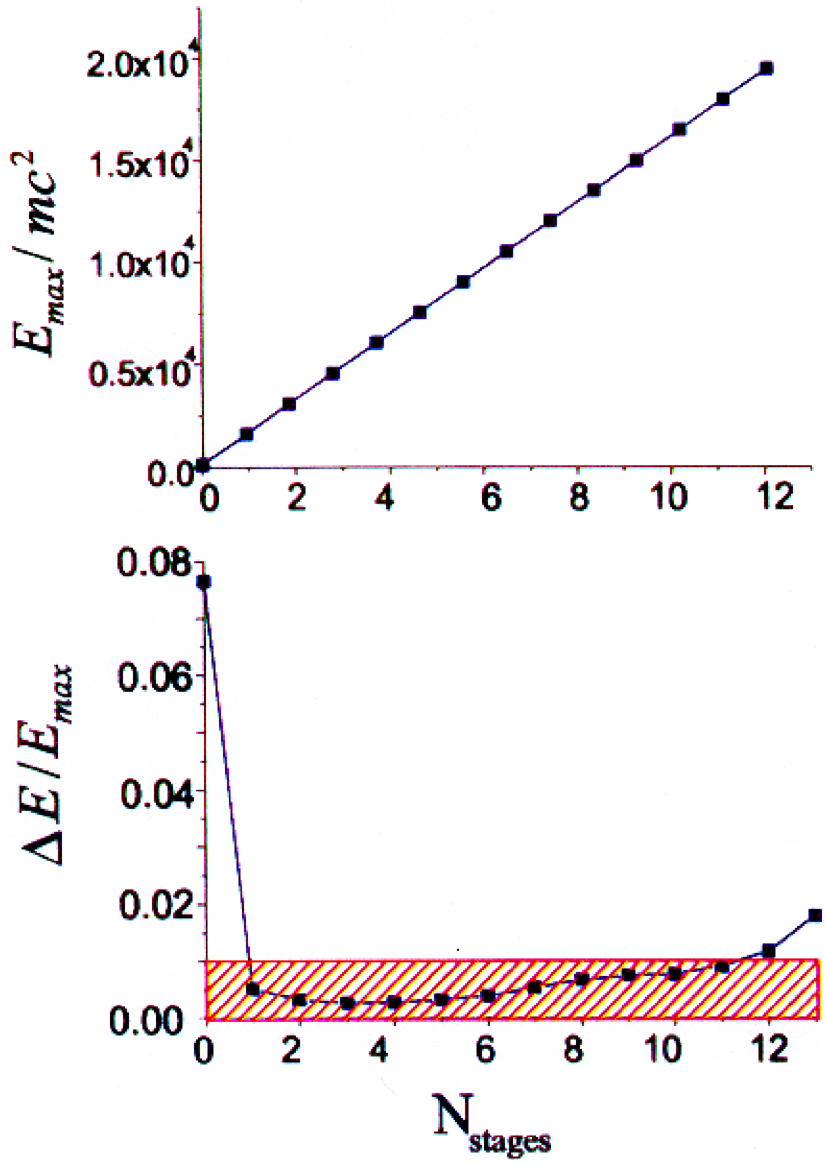
plasma parameters: λ_p=800 μm, $k_p R_{ch}$=14.3

bunch paramaters: E_{inj}=5 MeV, $\Delta E/E$ 1.5%, ε=0.6 mm.mrad,

L_{b0} = 30 μm (100 fs), r_{Lo} = 25 or 50 μm

wakefield amplitude: ϕ_{max} = 0.04 or 0.19

Multi-stage monochromatic LWFA with prebuncher



CO_2 laser (per each stage): P_L=50 TW, τ_L=1 ps, a^2=0.5

plasma parameters: λ_p=800 μm, k_pR_{ch}=14.3

bunch paramaters (before bunching stage):

τ_{b0}=100 fs; r_{b0}=50 μm, ε=0.6 mm.mrad

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Feasible high repetition rate regimes for picosecond CO_2 lasers

- 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)

Short Pulse Amplification by Raman Scattering

- **Three-wave interaction**

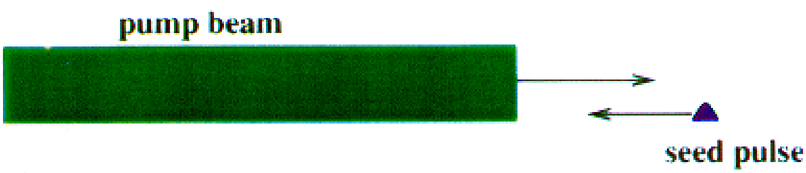
Pump a_1. Signal a_0. Plasma Wave $f = eE_z/mc\omega_p$

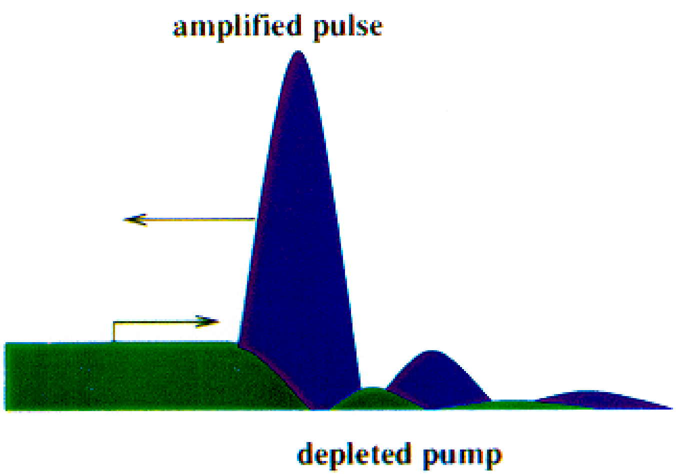
- **Resonant excitation of Plasma Wave**

Laser detuning $\Delta\omega = -\omega_p$

- **Plasma Wave linear $\Rightarrow$ no wavebreaking**

- **Total Pump Depletion**

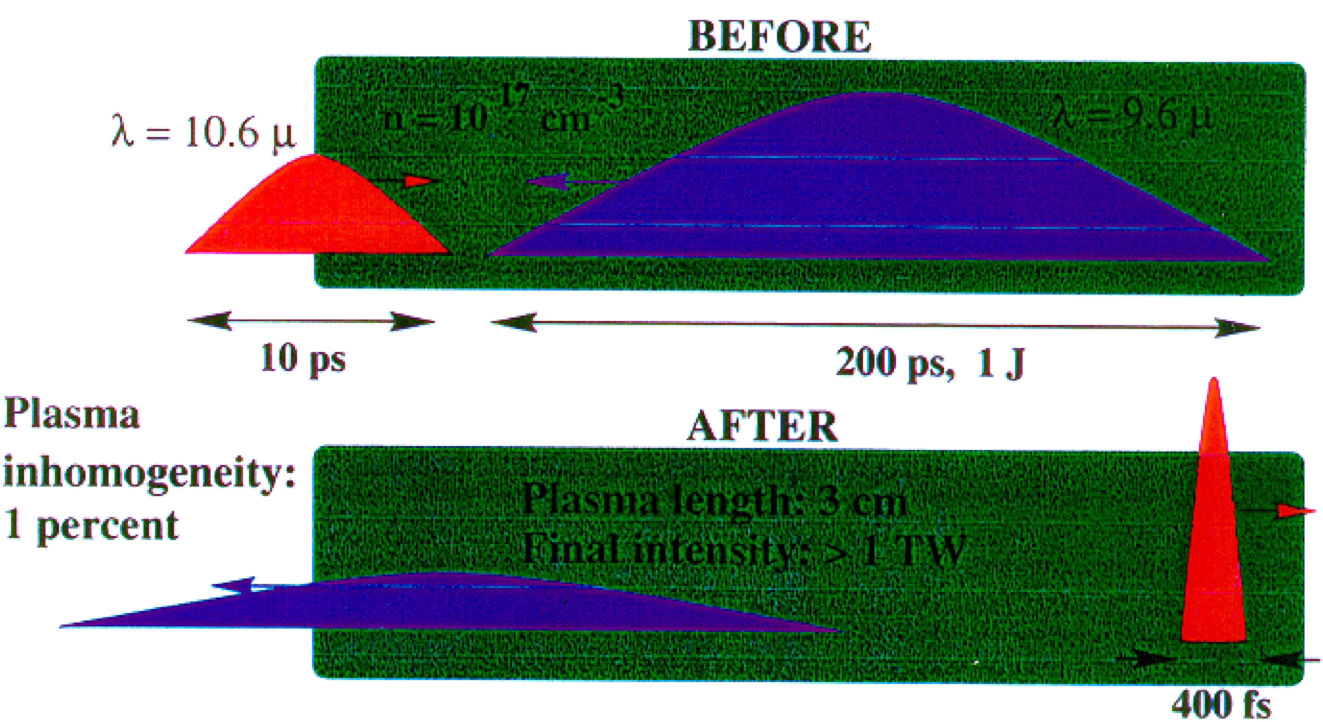




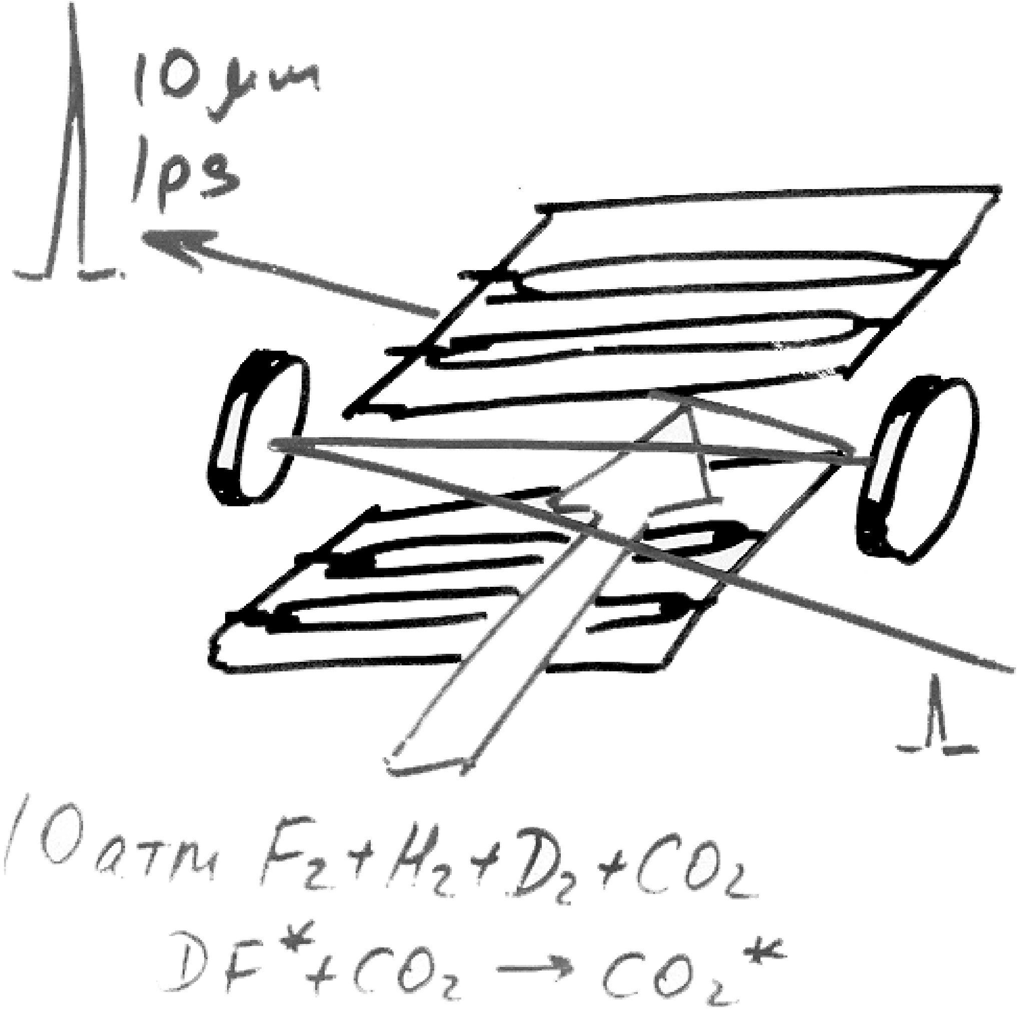
Further Compression of a Sliced Pulse by RBS

- Two-color amplifier which produces short pulse ω_0 and pump pulse $\omega_0 - \Delta\omega$
- Short-pulse duration $\tau_0 \gg (1/\Delta\omega)$
Long-pulse duration $\tau_p = 2L_{\rm pl}/c$
- Plasma of resonant density $n = m\Delta\omega^2/4\pi e^2$

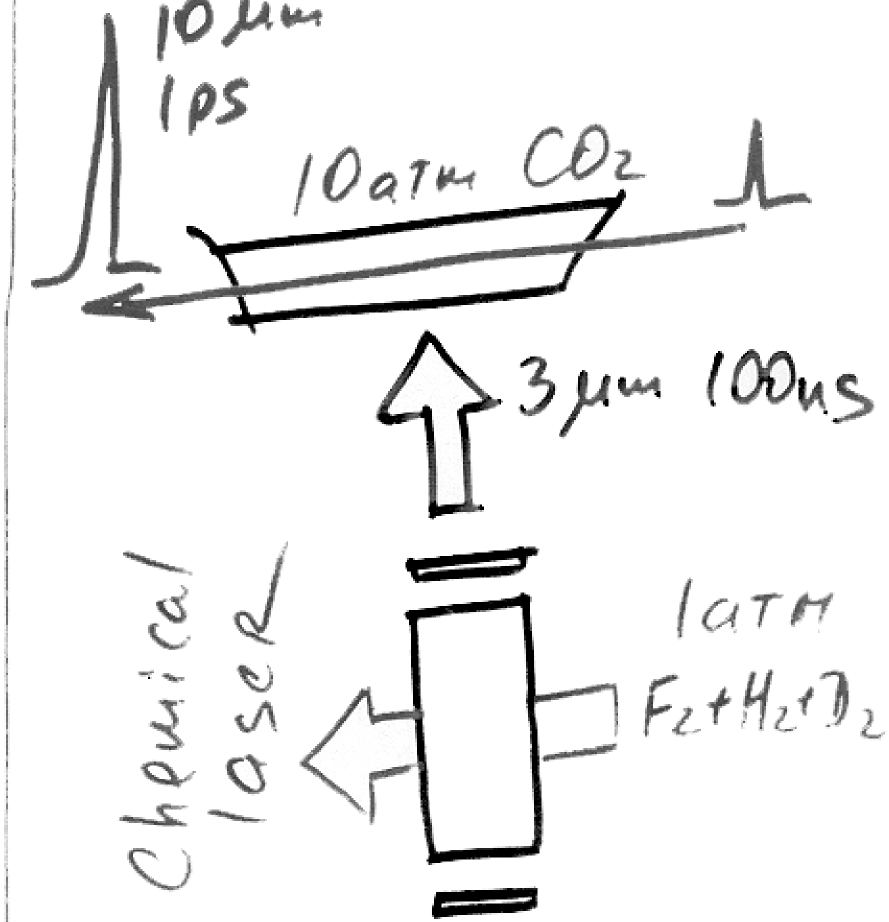
What can be done at ATF



Compression via superradiant amplification impossible: $\tau_0 \gg \dfrac{1}{\omega_p}$. **Note:** In Raman regime seed pulse rapidly contracts $\propto z^{-1}$.



CO2 laser with direct chemical pumping



CO2 amplifier with optical pumping by Chemical laser

Gas discharge pulsed power circuit with solid state switches

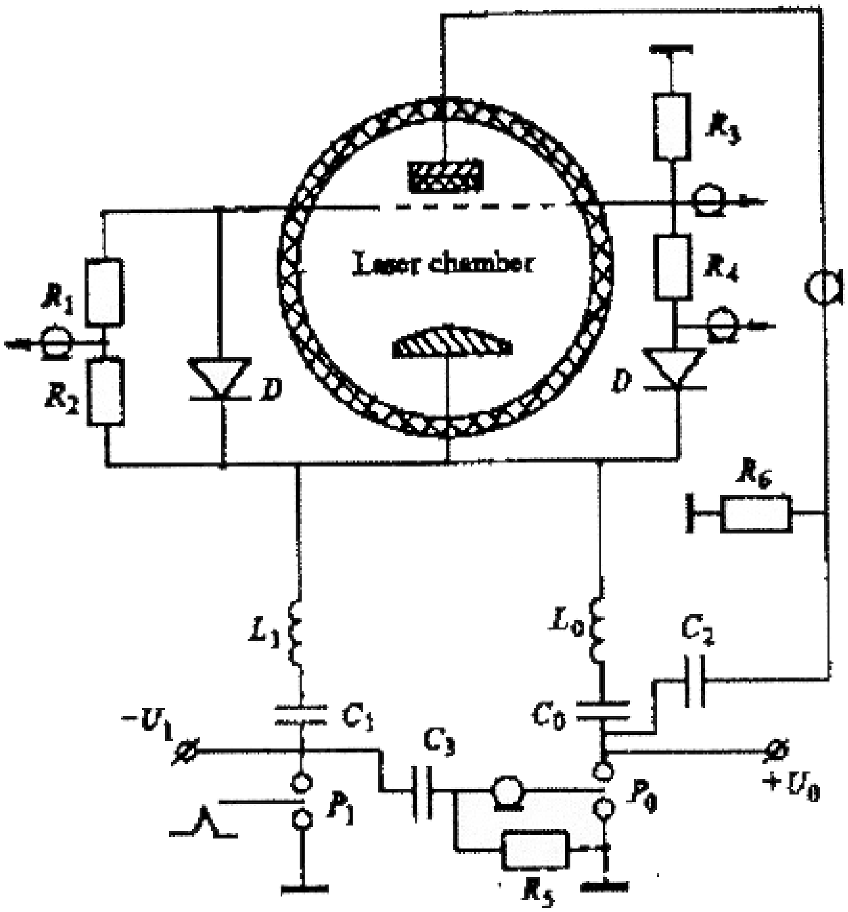


Fig. 1. Schematic of the transverse discharge laser. D: semiconductor diodes; P_0, P_1: RU-65 spark gaps; C_0, C_1: capacitance of the main and driving circuits, respectively; C_2: preionization capacitor; C_3: capacitor starting P_0; L_0, L_1: the circuit inductors; R_1–R_6: voltage divider, resistive shunts, and charging resistors, respectively.

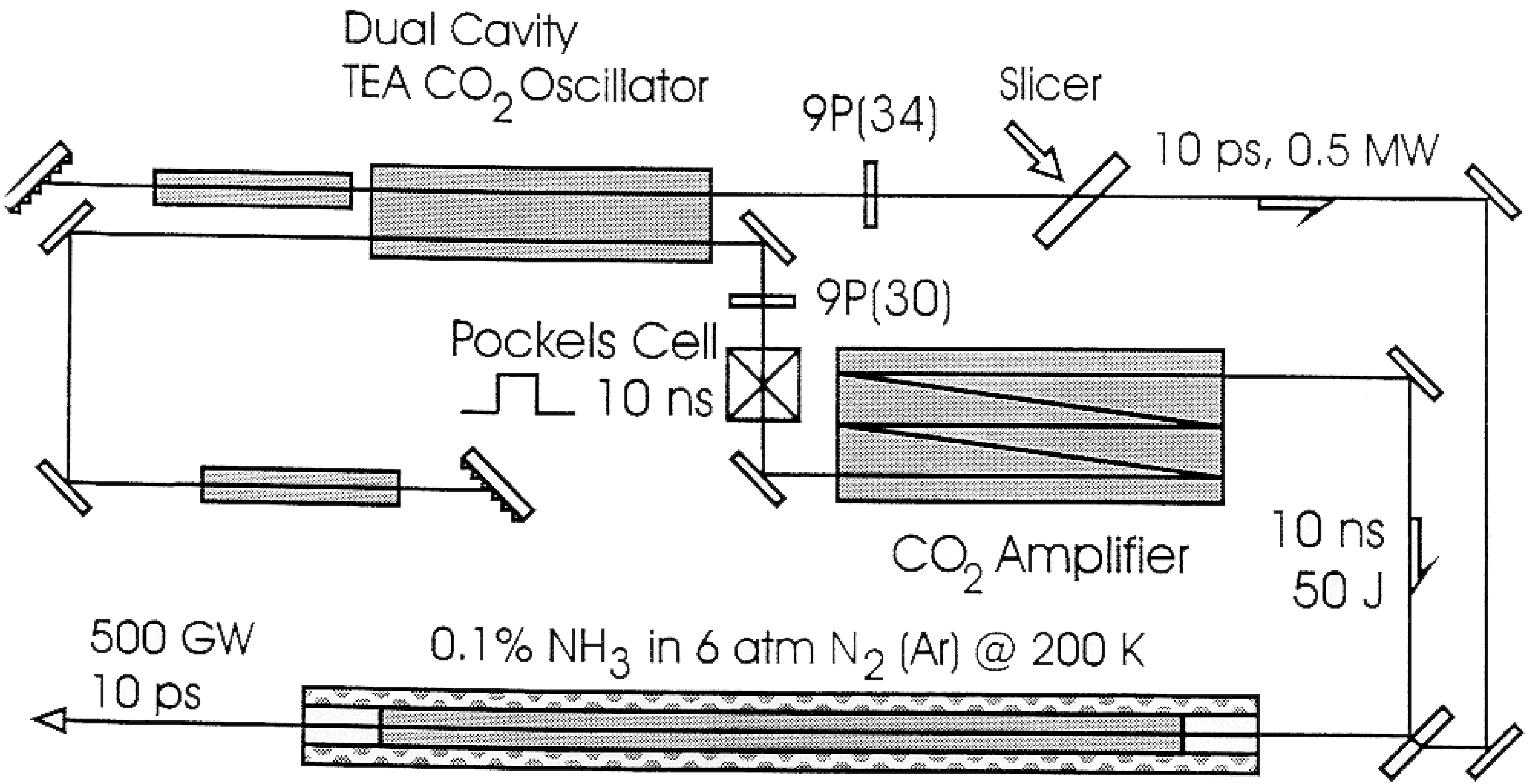
Semiconductor switches transmit current up to 8 kA and withstand the voltage up to 120 kV. They operate at 1 kHz and higher with switching time ~ 10 ns, can be placed in series and in parallel. Thus, for 500 kV and 100 kA we need about 60 switches.

Among other problems to solve:

high-speed gas circulation at 10 atm

high-speed vacuum pumping of x-ray tube

NH_3 Amplifier

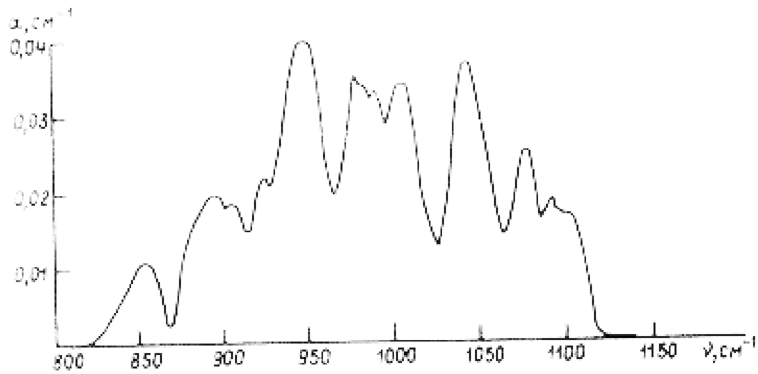


Predicted: 60 dB gain at 3 J/cm^2, 10 ns pump CO_2 pulse*

*[J.D. White and J. Reid, IEEE J. Quant. Electron., vol.29, 201 (1993)]

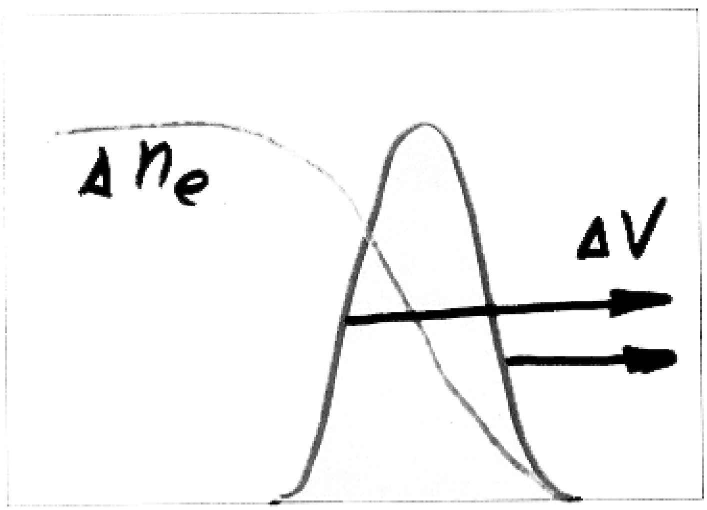
Towards Femtosecond CO_2 Laser Pulses

Gain bandwidth broadening



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 (e.g., V. Gordienko, et. al., 1991)

Pulse chirping in ionized gas



$\Delta V \propto \Delta n_e / n_{cr}$,
ionization $\Delta n_e \propto \lambda^2$,
$n_{cr} \propto 1/\lambda^2$, hence, $\Delta V \propto \lambda^4$.
That is why self-chirping in gas is practical only with CO_2 laser.
According to P. Corkum pulse shortening from ~1 ps to ~**150 fs** is possible

High energy 10-100 J capability of CO_2 laser permits ~PW from a relatively compact amplifier.