ATF Program Advisory Committee & ATF Users' Meeting

April 2-3, 2009 · Brookhaven National Laboratory

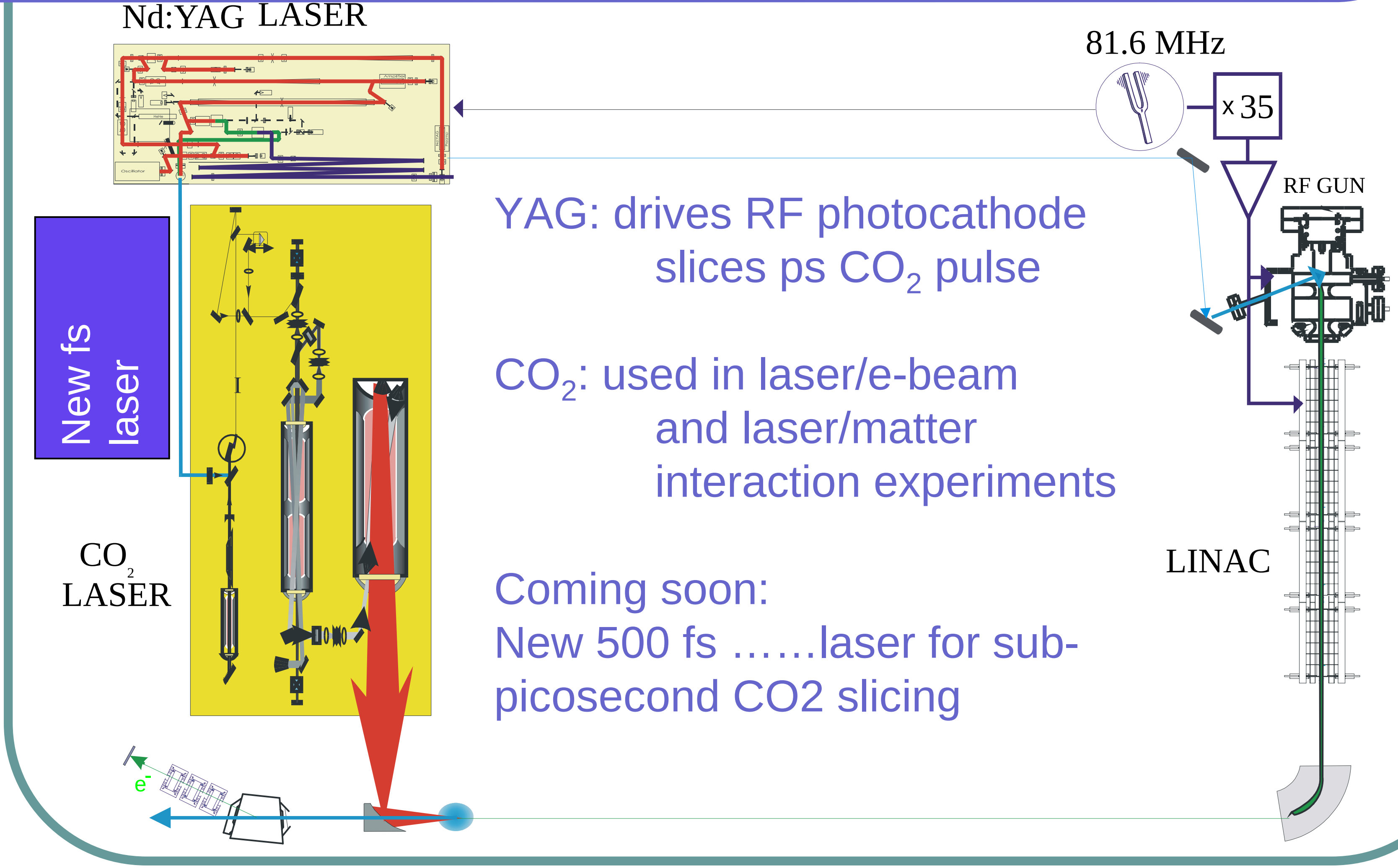
ATF CO_2 LASER

back to basics
present status
research highlights

Igor Pogorelsky

BROOKHAVEN
NATIONAL LABORATORY

ATF block diagram



YAG: drives RF photocathode
slices ps CO_2 pulse

CO_2: used in laser/e-beam
and laser/matter
interaction experiments

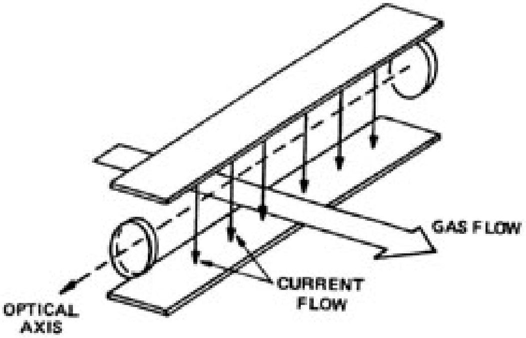
Coming soon:
New 500 fs ……laser for sub-picosecond CO2 slicing

ATF laser personnel

Igor Pogorelsky	CO_2 laser and experiments support
Mikhail Poliansky	LDRD Postdoc, simulations, CO_2 diagnostics
Marcus Babzien	YAG laser, general optical diagnostics
Daniil Stoliarov	Post-doc, fs solid-state laser
Karl Kusche	laser safety, computer controls
Vitaly Yakimenko	global laser strategy

+ ATF computer engineer, electronic engineer, designers, technicians

Industrial CO_2 lasers



- Up to 100 kW average power
- Operate at low pressure <<1 atm
- Bandwidth ~P (10 atm supports a picosecond pulse)

Ultrafast gas lasers require high pressure

Inverse Fourier Transform for discrete spectrum results in a train of discrete pulses

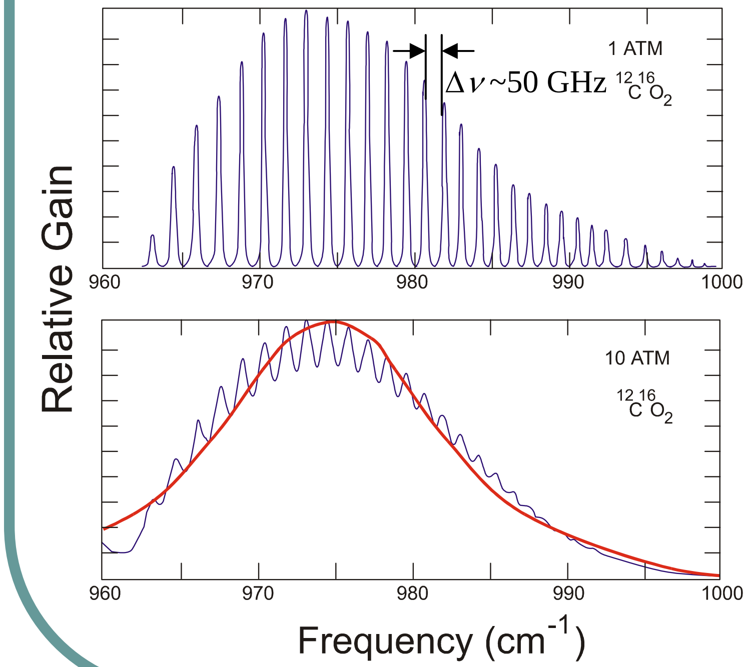
$$f(t)=\sum_{j=0}^{n} F_j(t)\exp[i2\pi(\nu_0+\Delta\nu\times j)t]$$

where $n \approx 1/\tau_0\,\Delta\nu$, τ_0 is the initial pulse width.

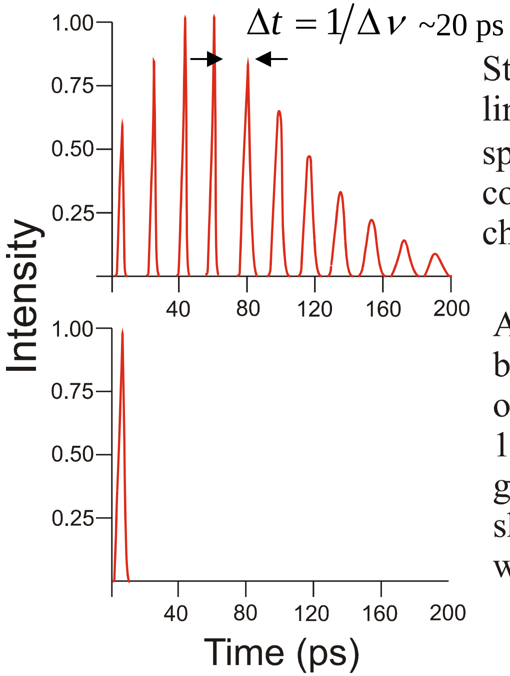
$$f(t)=\sum_{k=0}^{m} f_k(t_0+\Delta t\times k)$$

where $\tau_k \approx \tau_0$, $m\approx 1/\tau_0\,\delta\nu$, $\delta\nu$ - rotational linewidth defined by pressure broadening.

Gain Spectrum



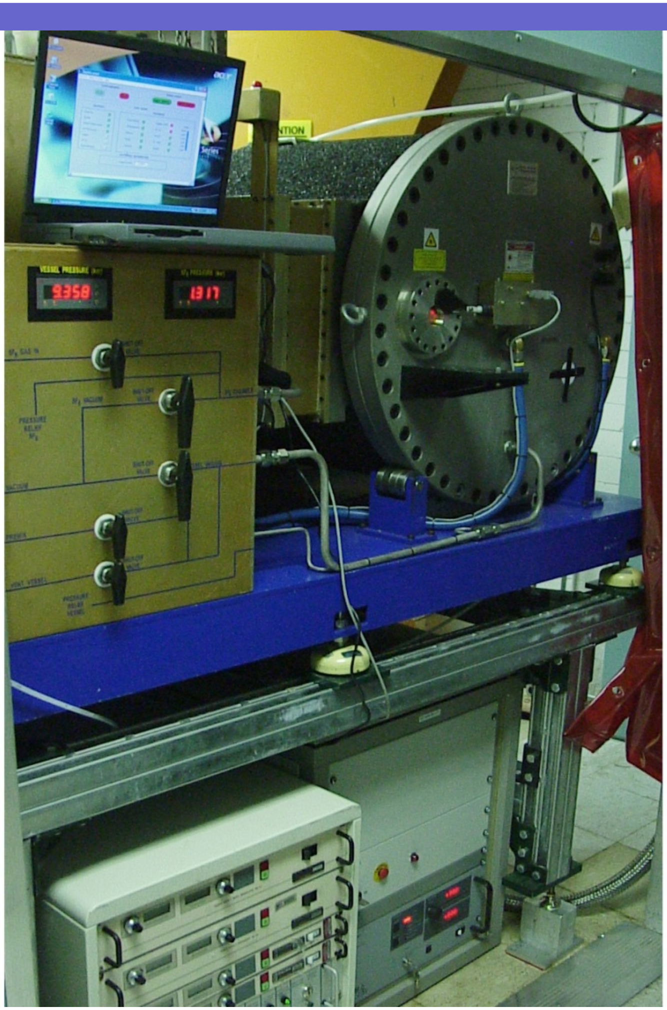
Amplified Picosecond Pulse



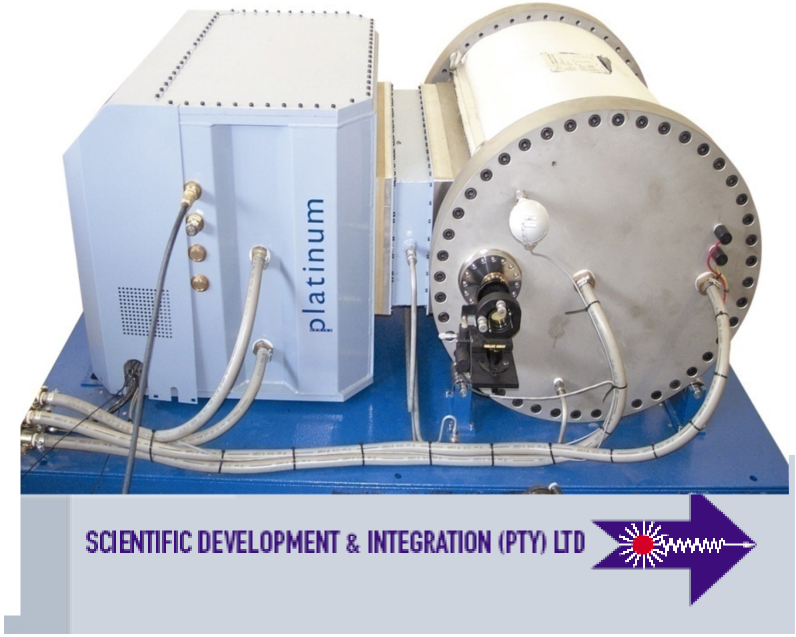
Strongly modulated rotational line structure of the CO_2 gain spectrum modifies the frequency content of picosecond pulses, changing their temporal structure.

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.

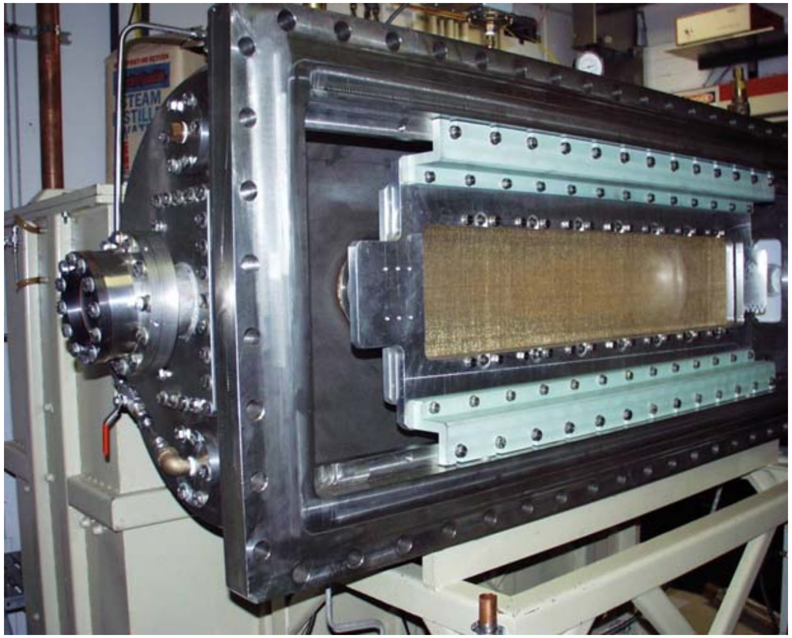
Commercially Available High-Pressure CO_2 Laser with UV-ionized discharge

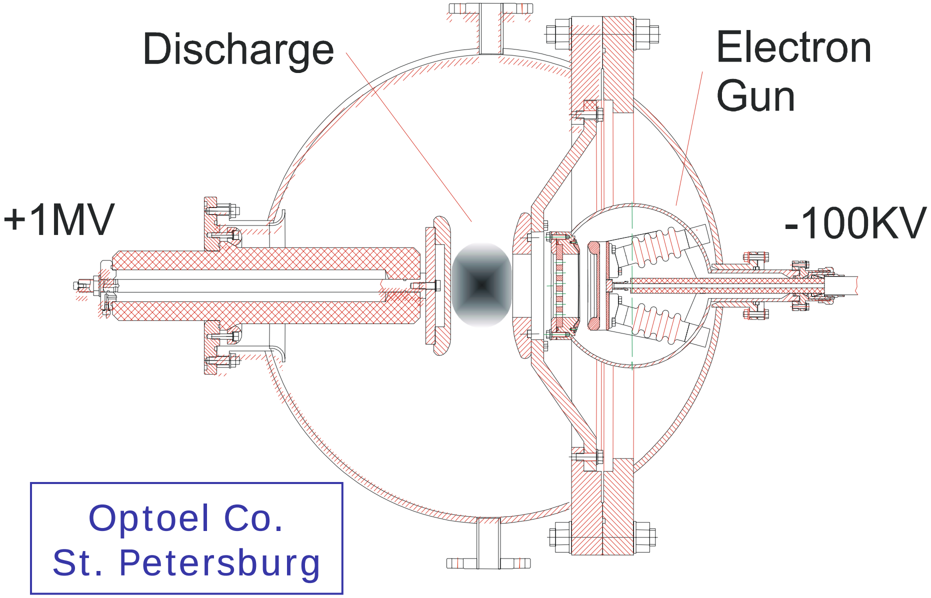


UV-preionized	
Pressure	10 atm
Beam Size	13 x 13 mm^2
Repetition Rate	20 -500 Hz
Pulse Energy	1.5 J
Average Power	750 W



Custom high-pressure x-ray ionized CO_2 amplifier operated at BNL/ATF





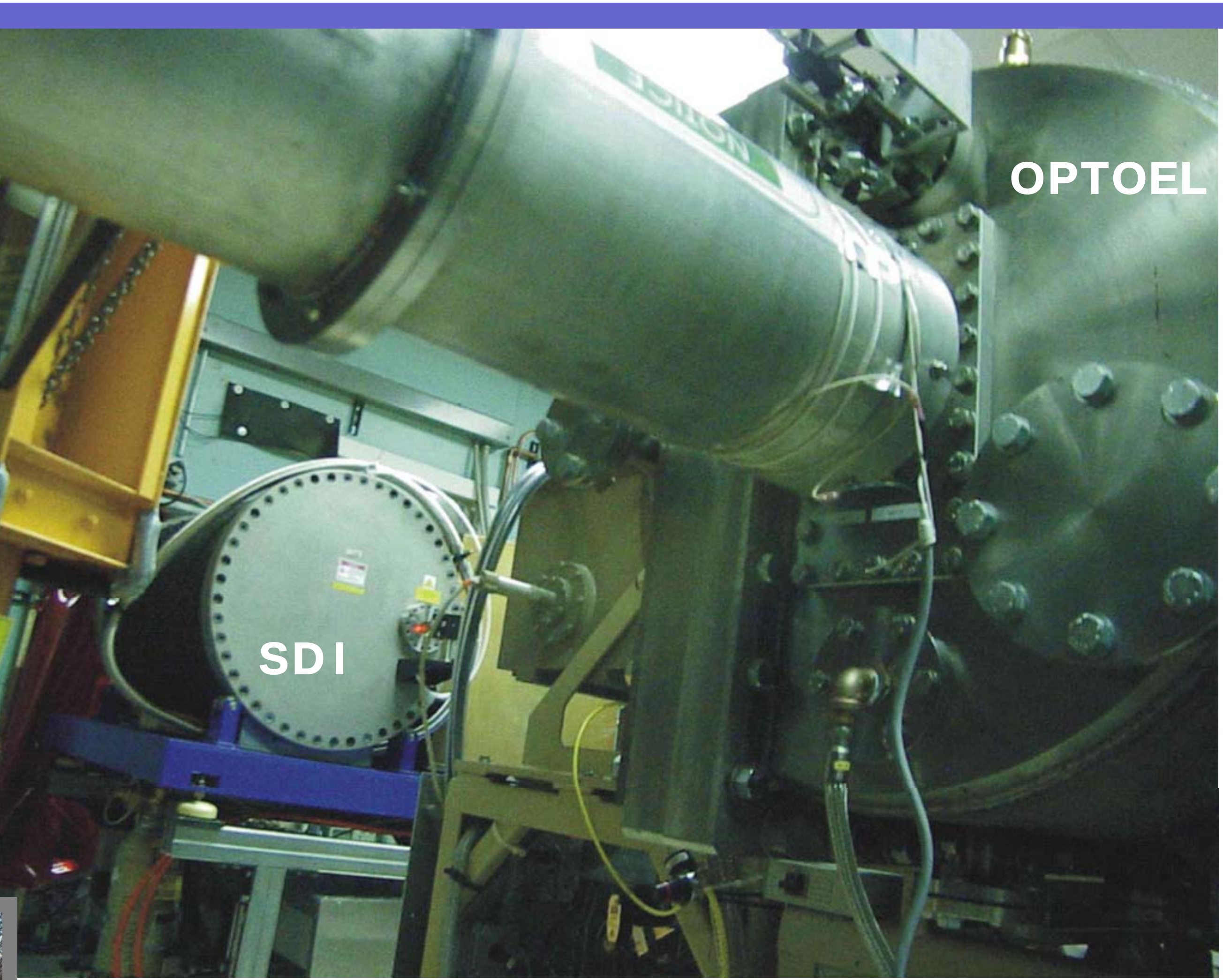
Optoel Co.
St. Petersburg

Amplifier cross-section diagram

Discharge	10x10x100 cm^3	Stored energy	$h\nu \times \Delta N = 10\ \mathrm{mJ/cm}^3$
Pressure	10 atm	Small-signal gain	$\sigma \times \Delta N = 2\%/\mathrm{cm}$
Voltage	1 MV	Saturation fluence	$h\nu/\sigma = 0.5\ \mathrm{J/cm}^2$

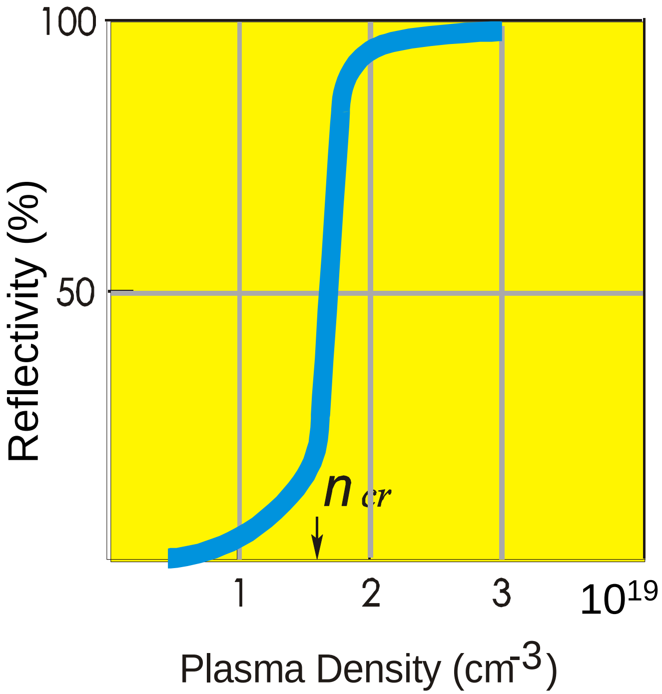
$h\nu = 0.1\ \mathrm{eV} = 1.6\times10^{-20}\ \mathrm{J}$, $\sigma = 3\times10^{-20}\ \mathrm{cm}^2$, $\Delta N = 10^{18}\ \mathrm{cm}^{-3}$

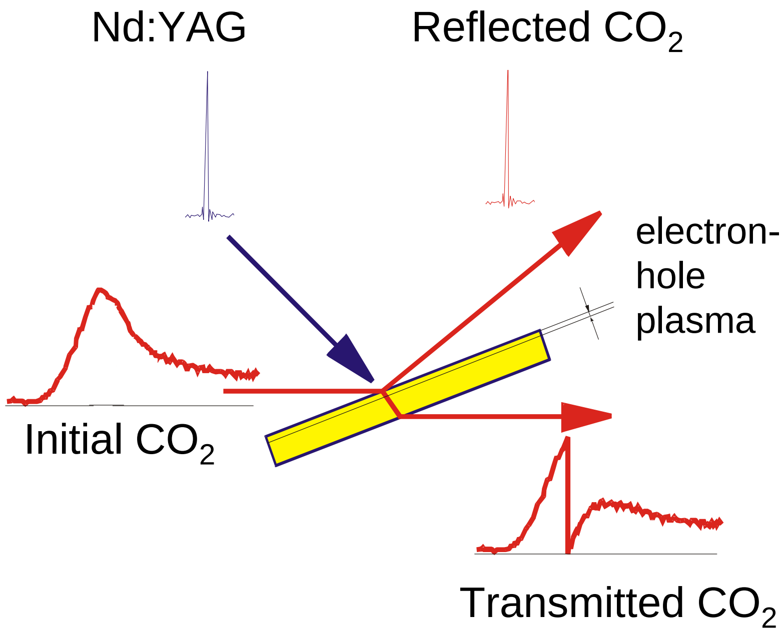
High-pressure CO_2 amplifiers operated at BNL/ATF



Methods of short pulse generation
Semiconductor optical switch

- Reflection by electron-hole super-critical plasma controlled by a short wavelength laser.

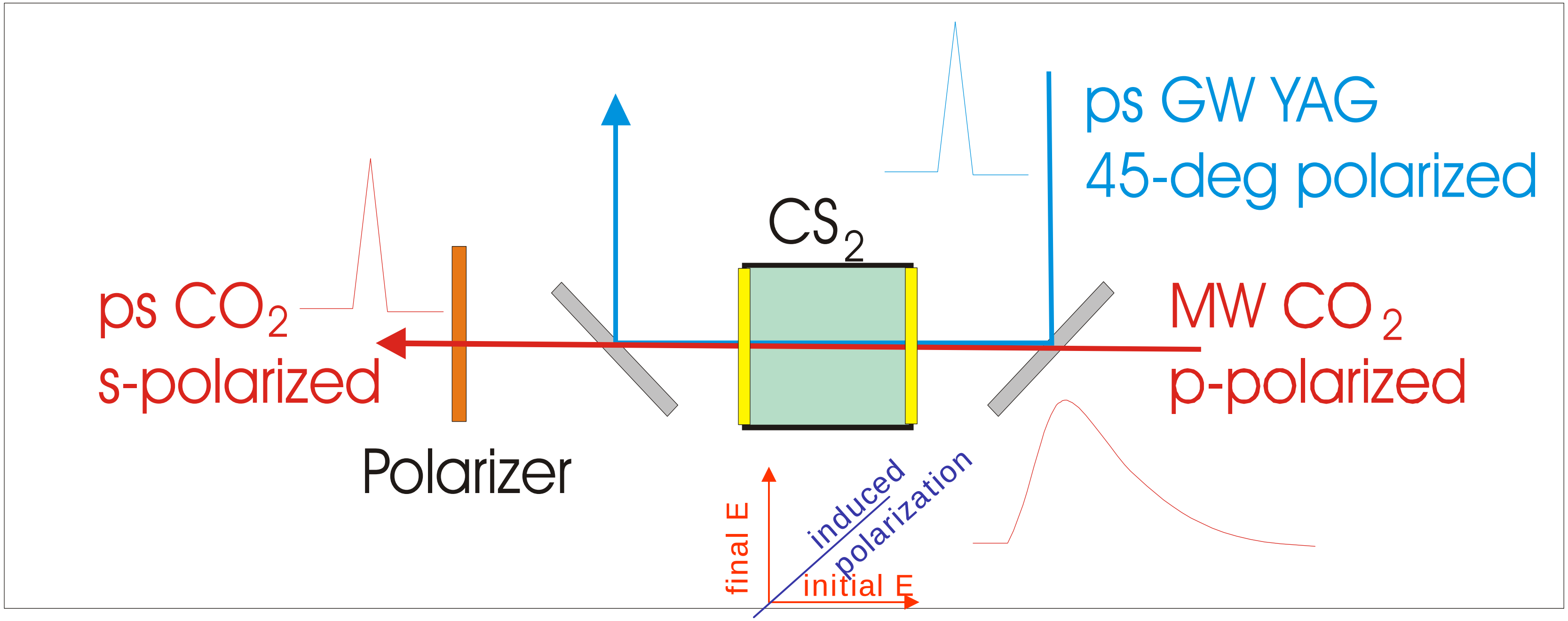




- Reflection lasts for 200 ps defined by relaxation of free carriers.
- Two switches allow to slice CO_2 pulse to the duration of a control pulse.

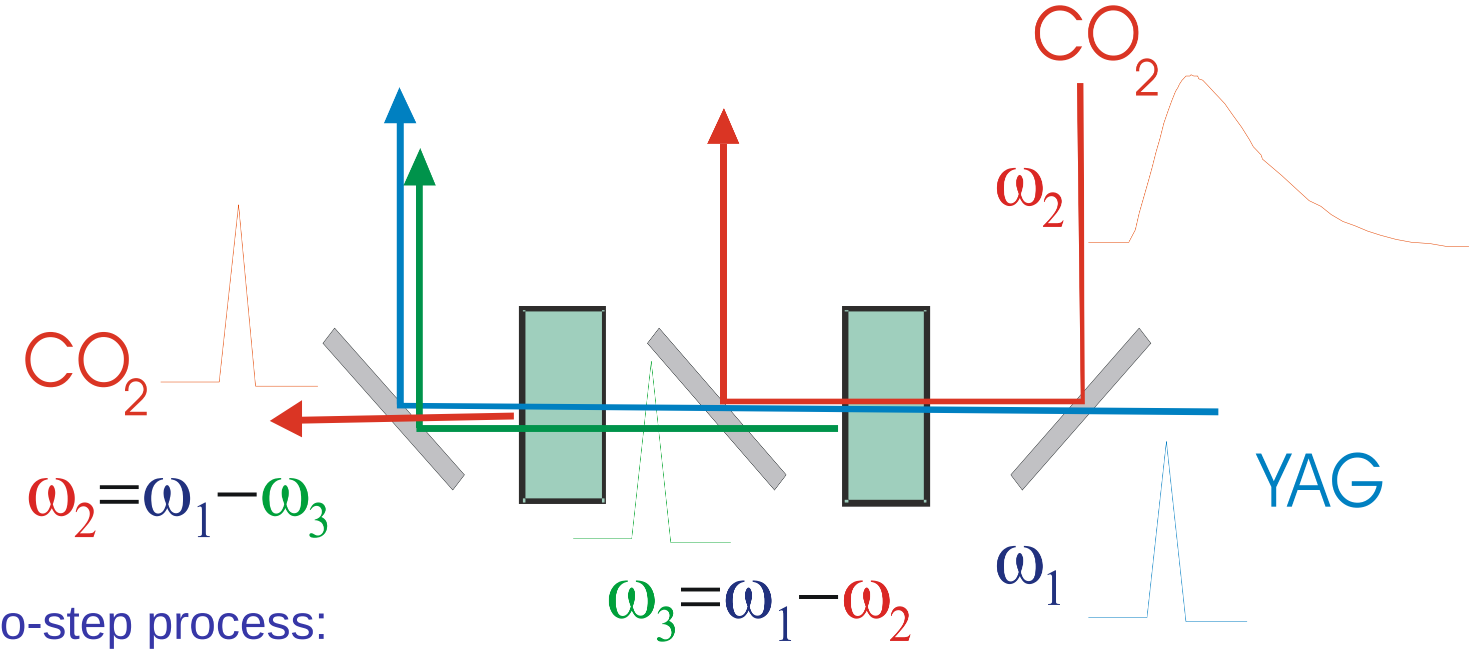
Methods of short pulse generation

Kerr effect



- A higher-power laser induces polarization in optically active CS_2 liquid.
- This rotates polarization of a portion of a CO_2 pulse overlapped with YAG.
- Relaxation of CS_2 molecules in 1-2 ps.

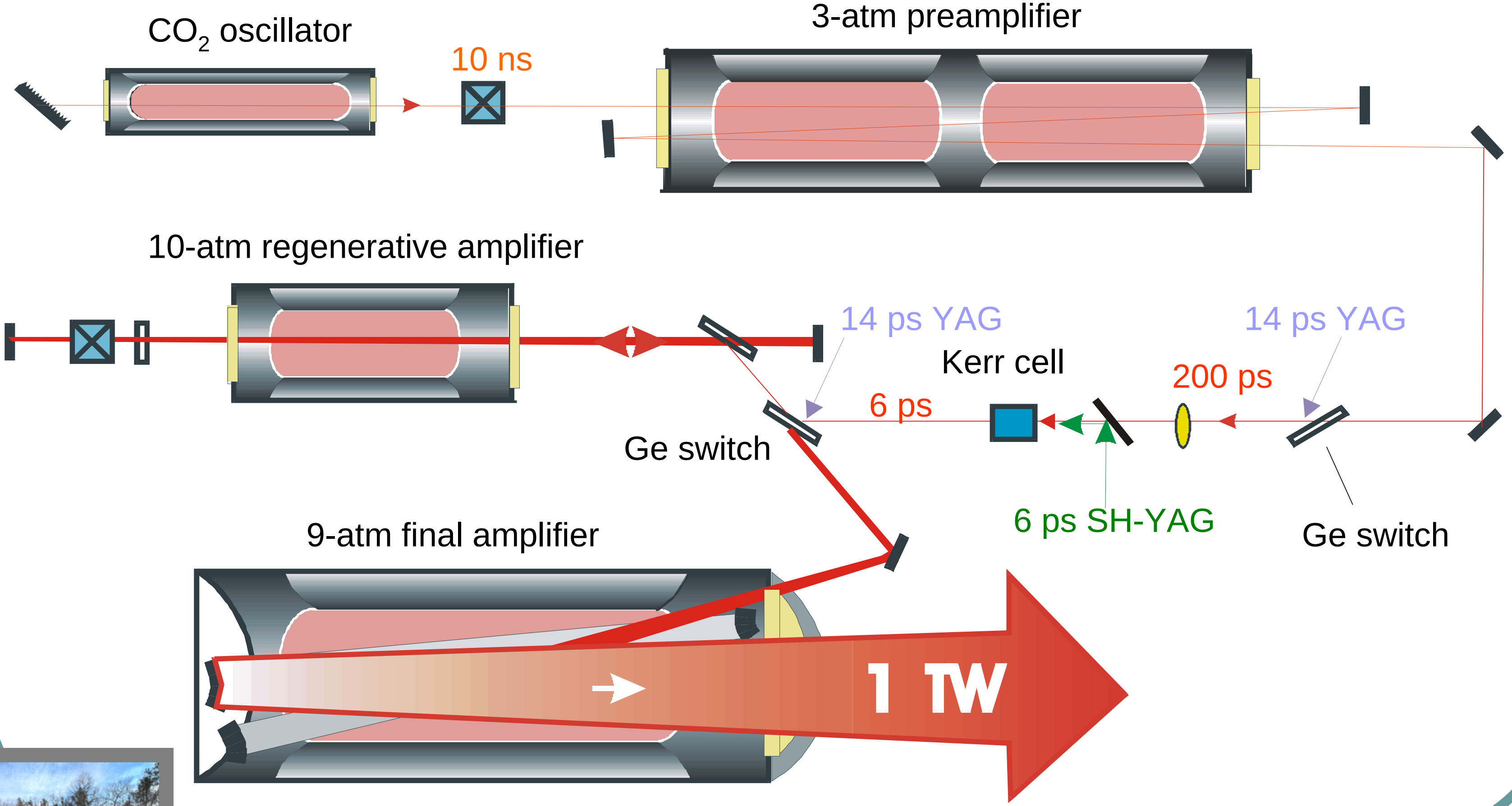
Methods of short pulse generation
Parametric generator



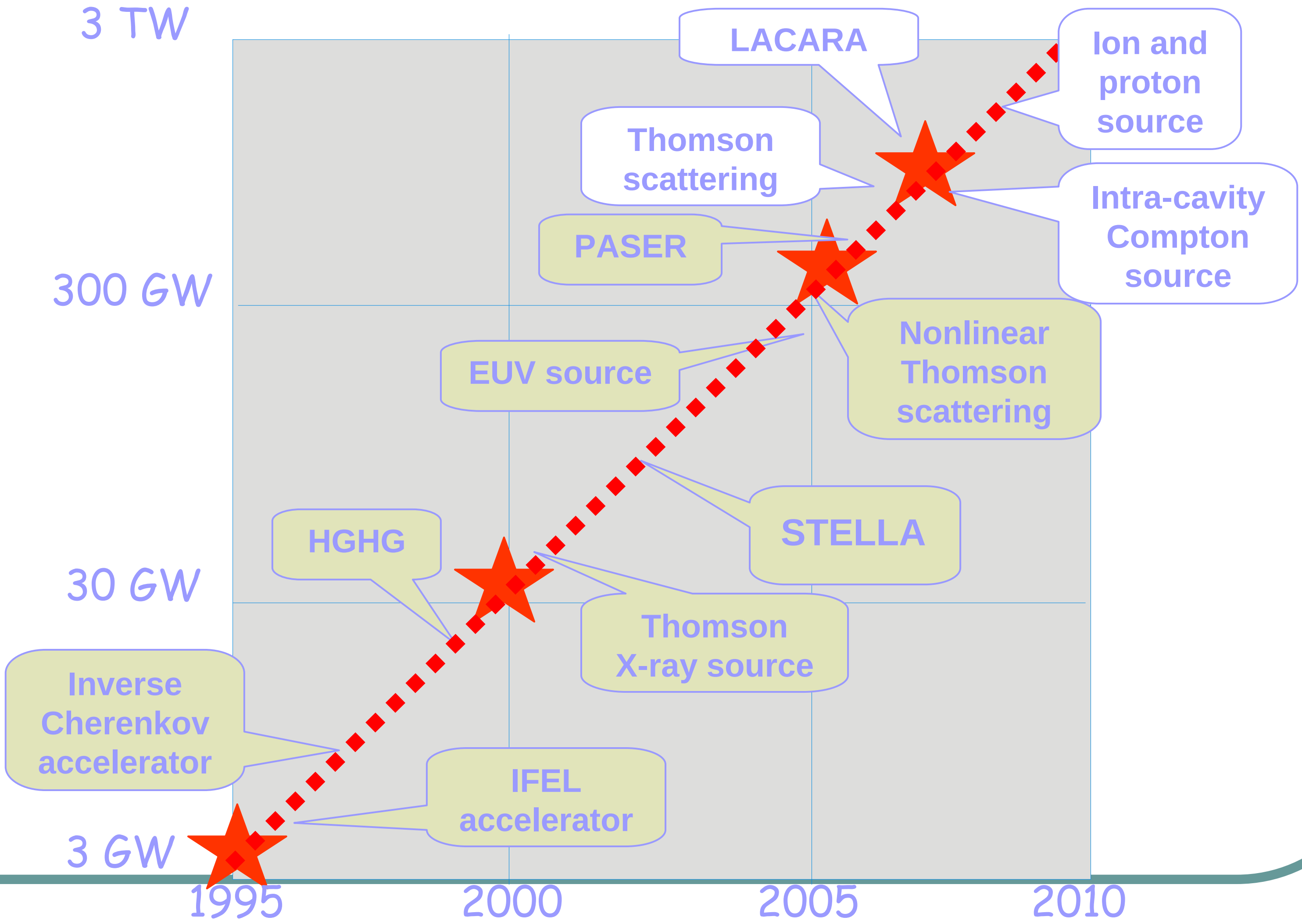
Two-step process:

- Mixing two laser beams in a nonlinear crystal with production of differential frequency.
- Mixing ω_3 and ω_1 with production of a CO_2 pulse at the duration of YAG or shorter.
- Insignificant stretch in thin crystals, 1 ps is possible.

CO_2 laser system delivers 0.5 TW, 6 ps pulses



ATF success story



Benefits from using CO_2 laser

ATF pioneers a *picosecond* CO_2 gas laser for strong-field physics applications.

This provides a new platform for exploring novel methods of particle acceleration and radiation sources.

CO_2 (λ=10 μm) advantages
as compared to solid-state lasers (λ~1 μm) :

- 10 times more photons per Joule
- favorable scaling of accelerating structures, better electron phasing into the field
- stronger ponderomotive effects at the same laser intensity

Long-wavelength benefits: better electron phasing into the field

Long-wavelength benefits: stronger ponderomotive effects

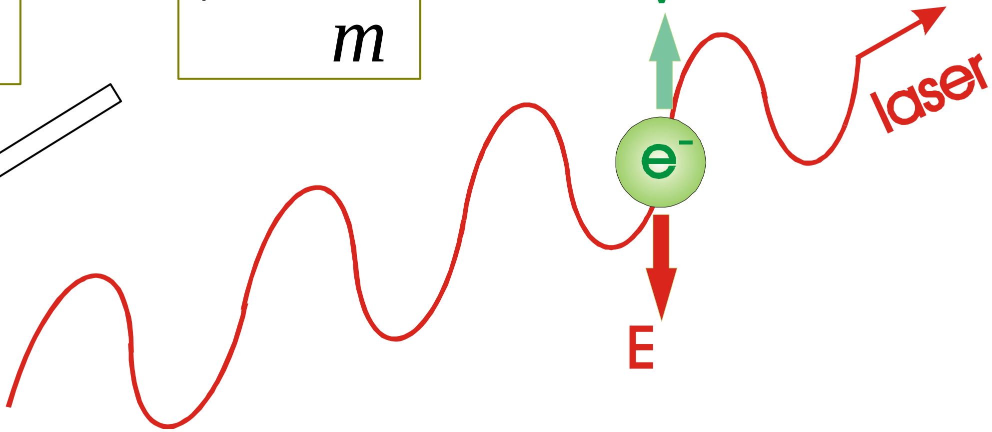
Energy of the electron quiver motion in laser field E

$$\boxed{\Phi = \frac{mv^2}{2}} \Rightarrow \boxed{v \sim \frac{\dot{v}}{\omega}} \Rightarrow \boxed{\dot{v} \sim \frac{eE}{m}}$$

$$\boxed{\Phi \sim \frac{e^2E^2}{2m\omega^2}}$$

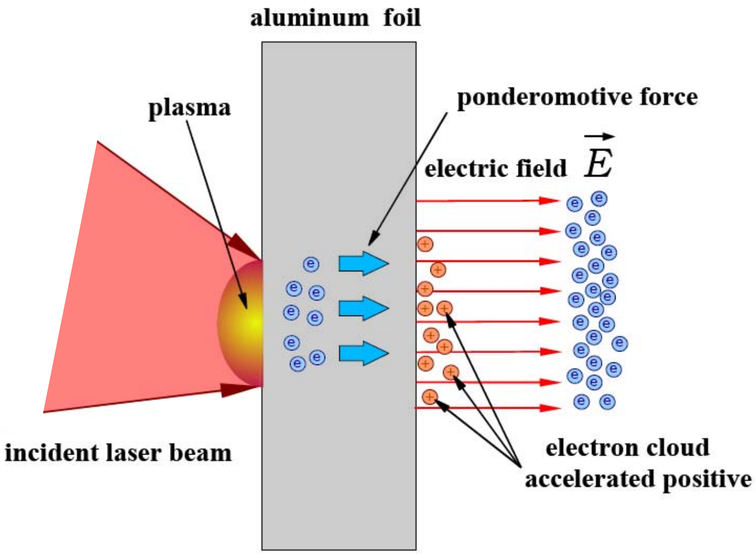
$$\Downarrow$$

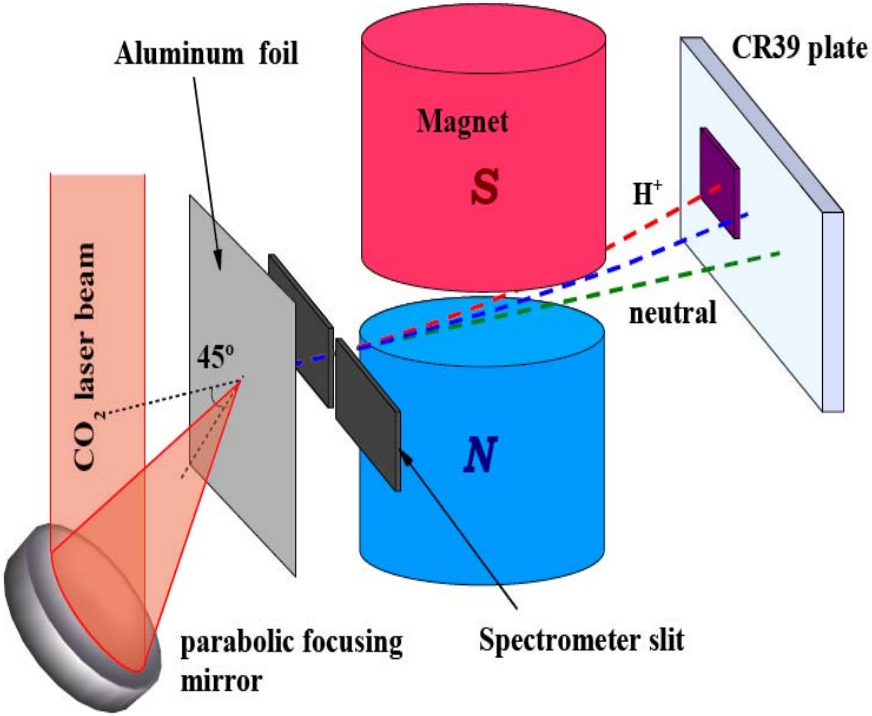
$$\boxed{\Phi \sim \frac{I}{\omega^2}}$$



note the ω^2 dependence

Proton accelerator

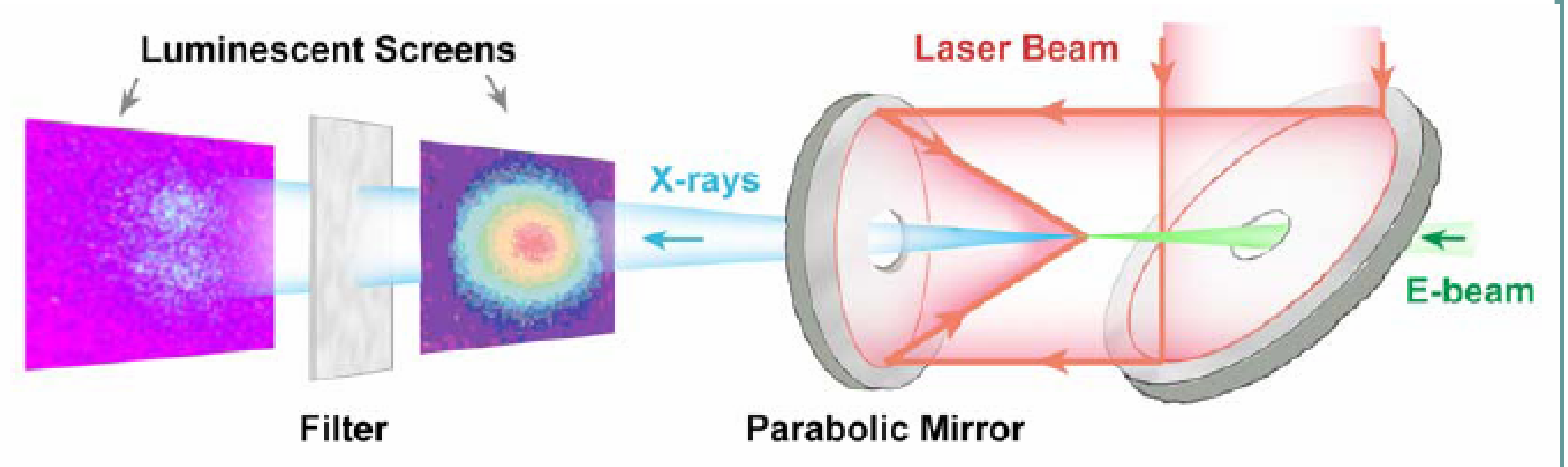




Production of fast electrons is the key.

- At the same power and energy, CO_2 laser will provide the same ponderomotive action within ~λ^2 (100 times) bigger area or ~λ^3 (1000 times) bigger volume.
- Accordingly, we expect that the number of accelerated ions would grow with λ.

Demonstration of record yield and 2nd harmonic in relativistic Thomson scattering



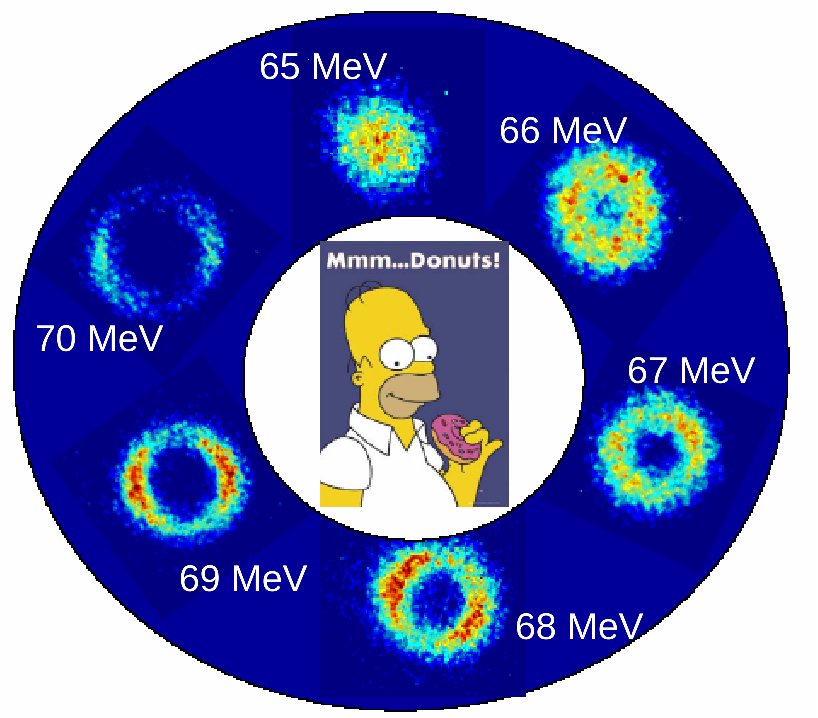
With 5 J CO_2 laser focused to $\sigma = 35\ \mu m$, we demonstrated record x-ray yield $N_x/N_{e-}\sim 1$ And 2nd harmonic in relativistic Thomson scattering

note that 10-μm laser produces 10 times more photons per Joule than 1-mm laser

$$\frac{N_x}{N_e} = \frac{N_L}{\pi w_0^2}\sigma_T$$

Spin-offs from earlier Thomson scattering experiments

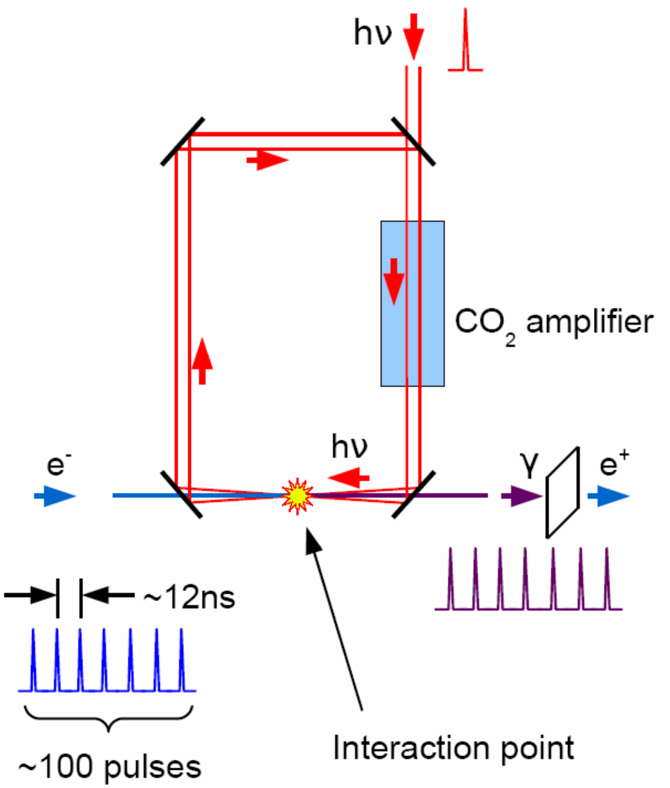
Parametric studies



credits to

UCLA

Intra-cavity gamma-source



Next laser talks

- Marcus Babzien “*Experimental support and instrumentation*“
- Mikhail Polyanskiy ”*Simulation and diagnostic tools for better understanding and upgrade of the CO_2 laser*“
- Daniil Stolyarov “*A femtosecond CO_2 front end based on frequency mixing with an Ytterbium laser*“
- Igor Pogorelsky “*CO_2 laser: Near-term plans*“