ATF Program Advisory Committee
and ATF Users' Meetings

April 4 - 6, 2007 · Brookhaven National Laboratory

Progress and Potentials of Ultra-Fast CO$_2$ LASERS

Igor Pogorelsky

Accelerator Test Facility

Outline

Introduction

- Success story
  - Basic principles

ATF Prospects

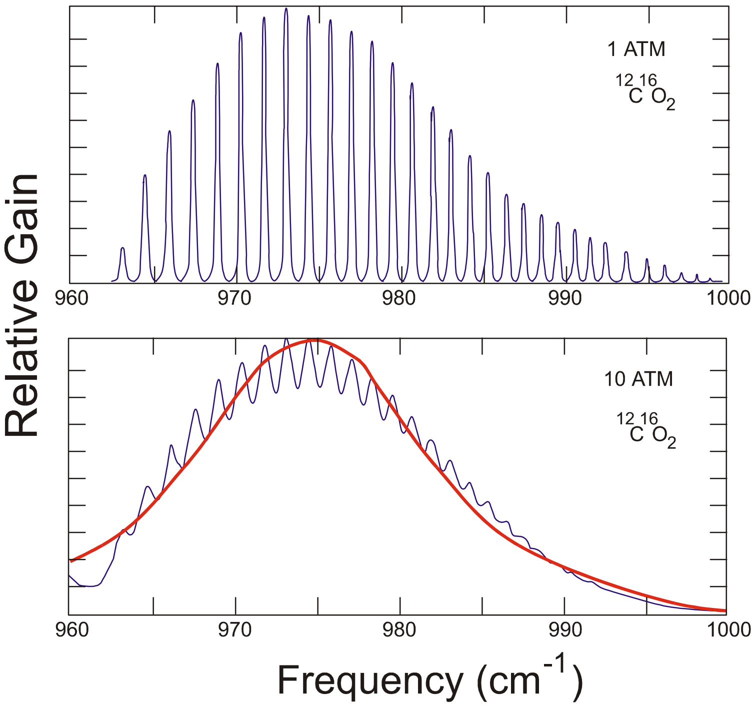
- Near-term increase of laser strength to a_0~4
  - Femtosecond regime
    - Multi-terawatts at linac's repetition rate

PW and high-repetition rate frontiers of CO_2 laser technology

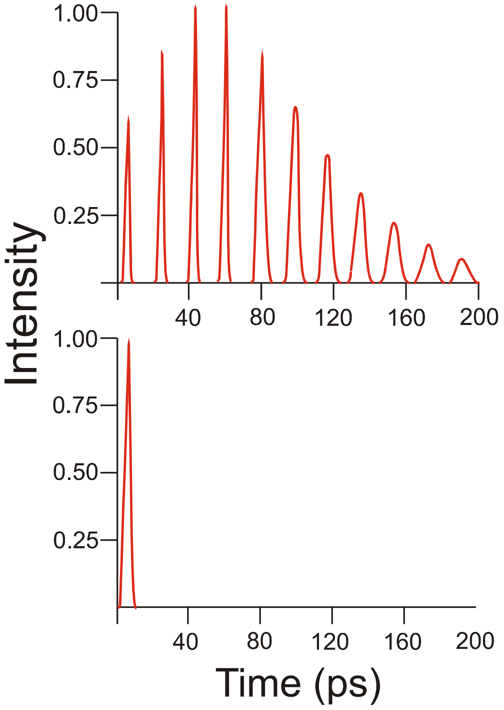
- PW via power broadening
  - Commercial 500 Hz lasers
    - Using intra-cavity beams

Bandwidth limited amplification of ps CO_2 laser pulses

Gain Spectrum



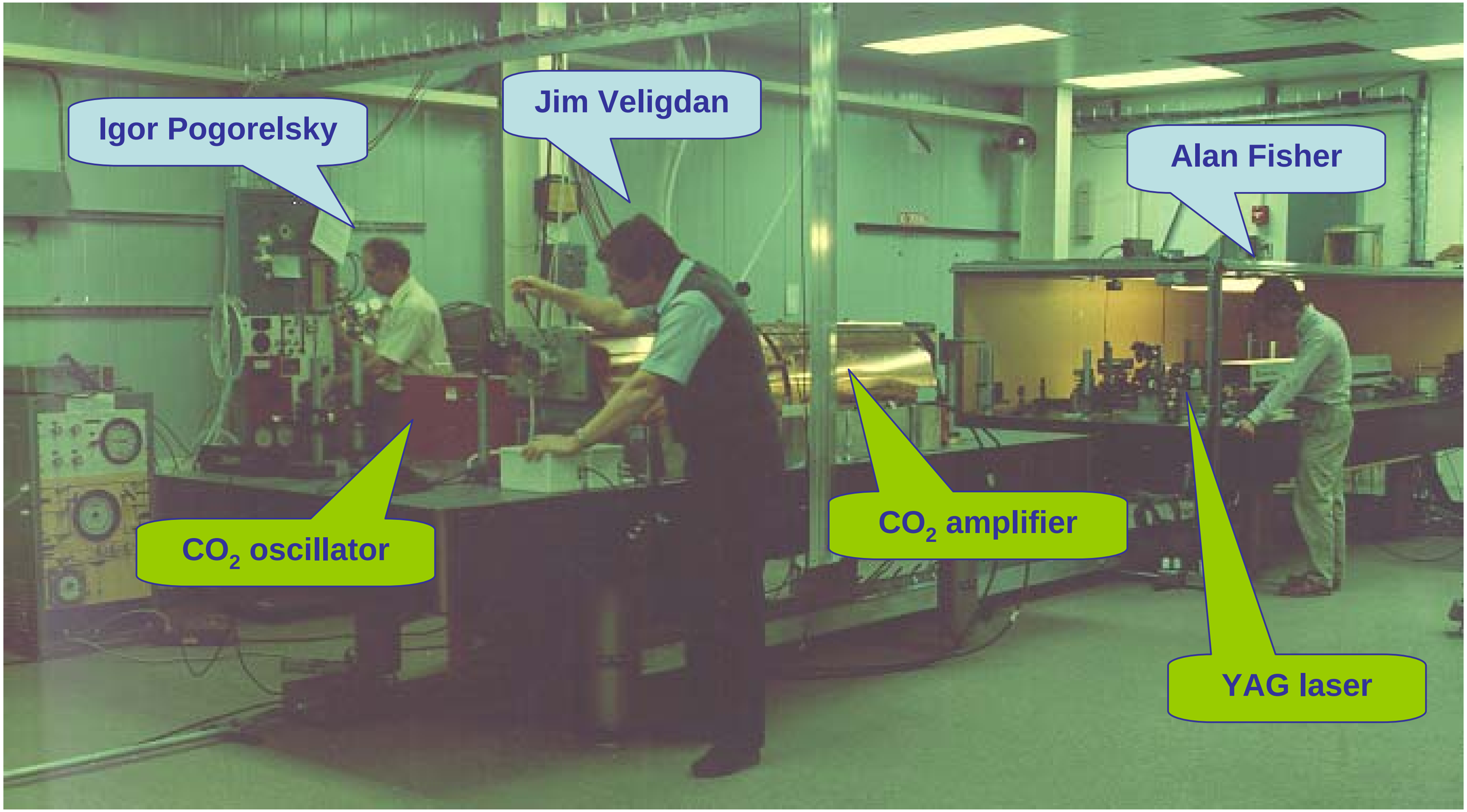
Amplified Picosecond Pulse



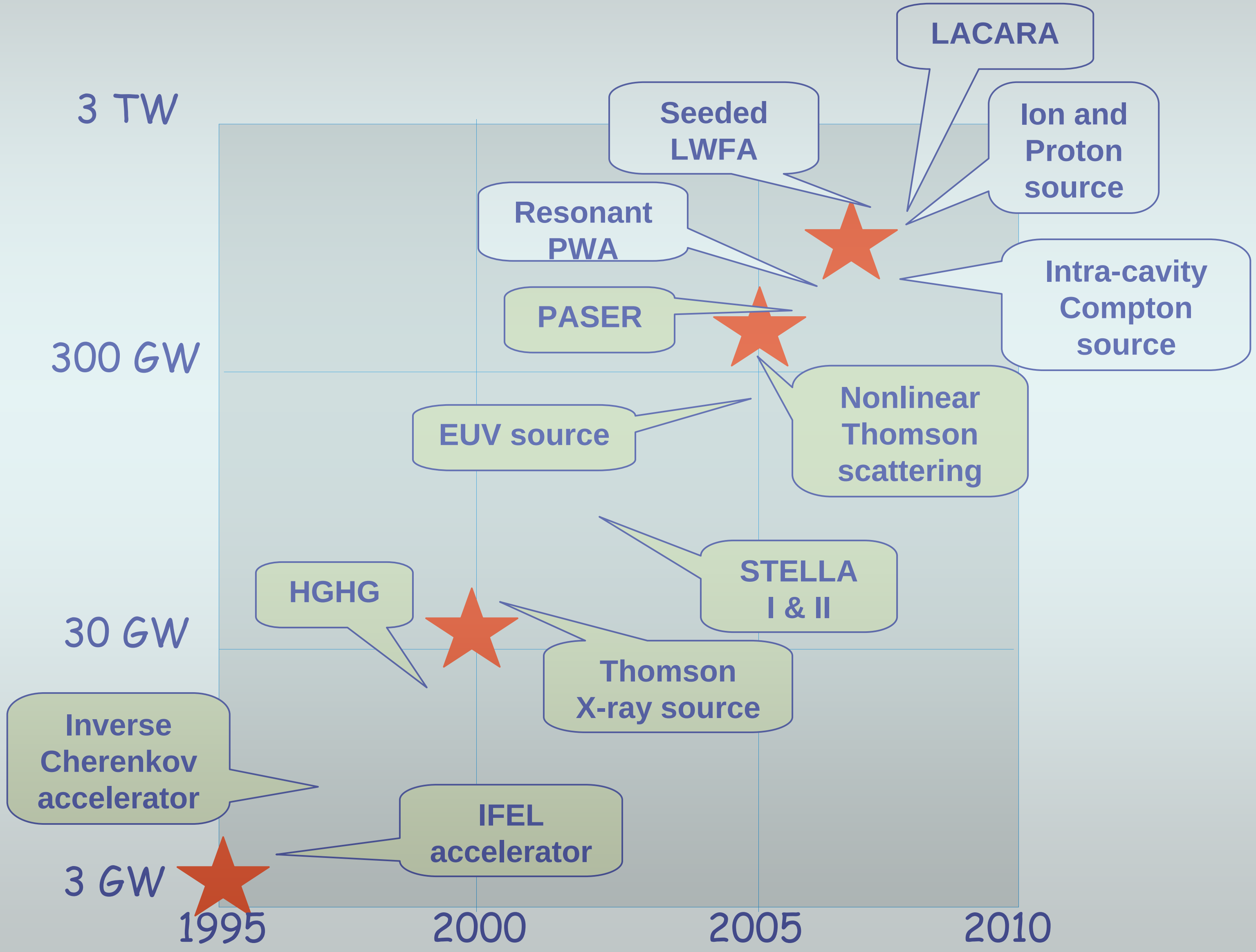
Strongly modulated rotational line structure of the CO_2 gain spectrum modifies the frequency content of picosecond pulses, changing their temporal structure.

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.

Prehistoric ATF laser system 1990



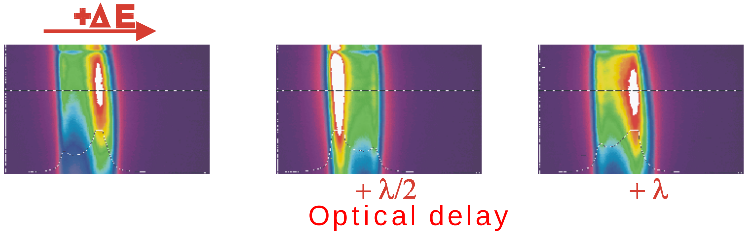
ATF Laser Success Story



Benefits of using long-wavelength (λ=10μm) CO_2 laser for non-relativistic processes:

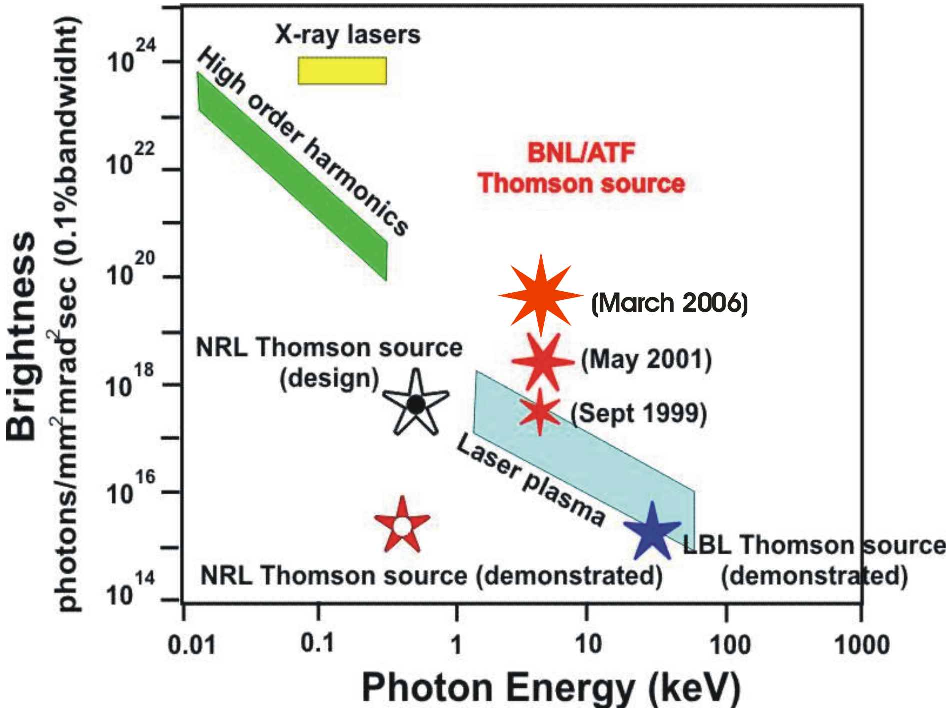
- **Combines advantages of high-quality conventional RF accelerators and high-gradient optical accelerators with λ =~1 μm**
  - **favorable phasing**
  - **structure scaling.**

Illustrated by STELLA - the first two-stage laser accelerator

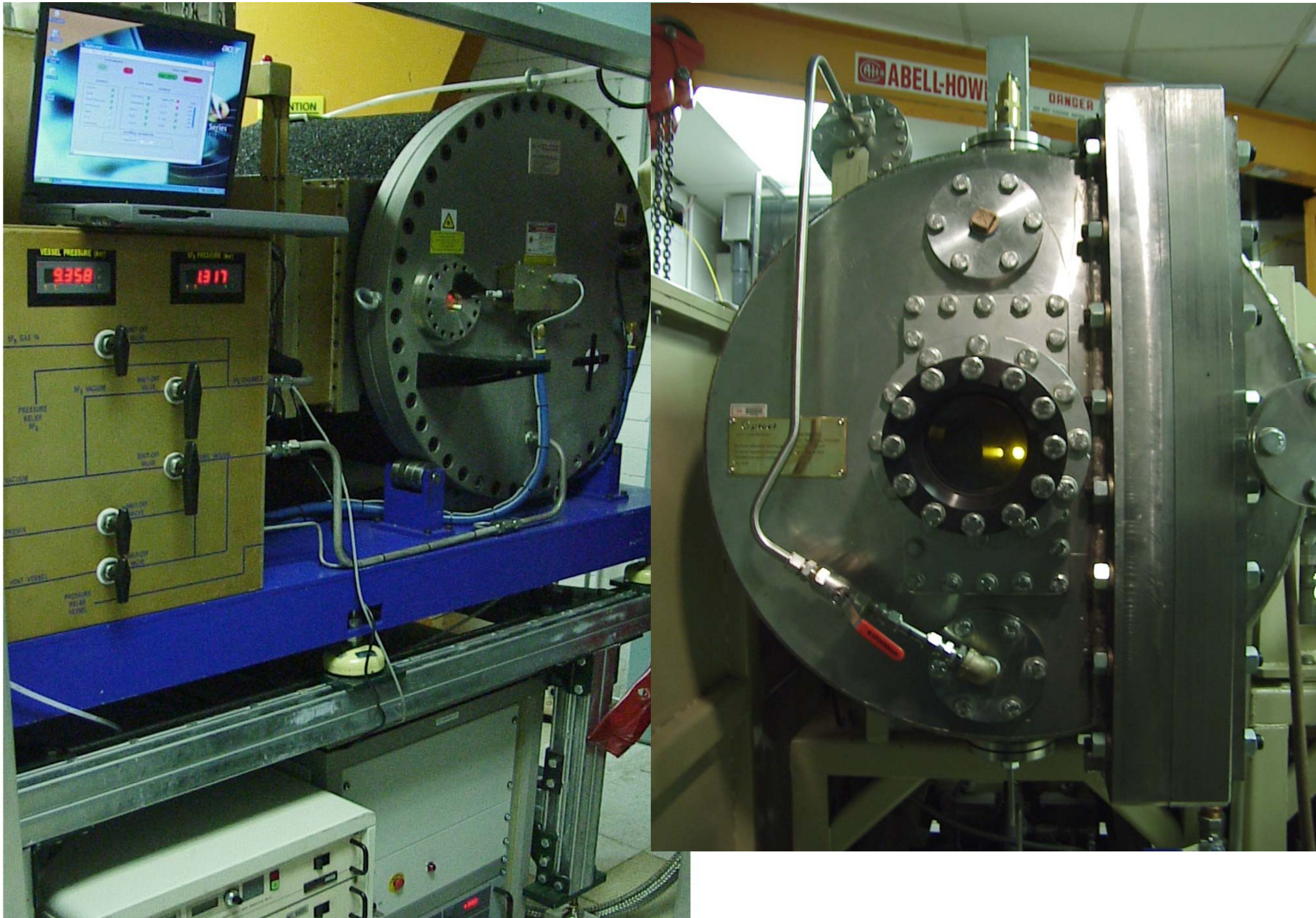


- **Number of laser photons per Joule of energy is proportional to λ.**

Illustrated by Thompson scattering experiment – presently the brightest Thomson x-ray source.



High-Pressure CO_2 Lasers



Solid state lasers help with picosecond pulse generation at CO_2 laser wavelength

Available methods:

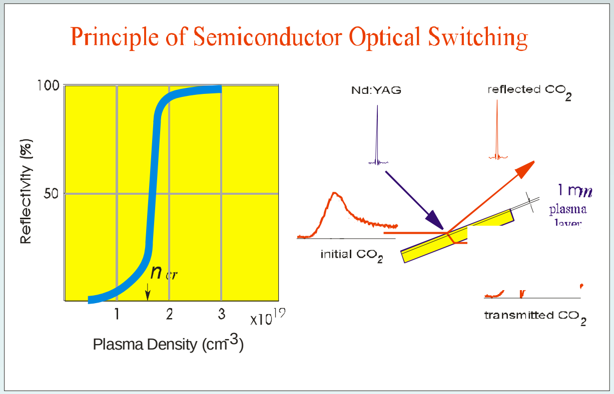
- Semiconductor optical switching

- Kerr effect in optically

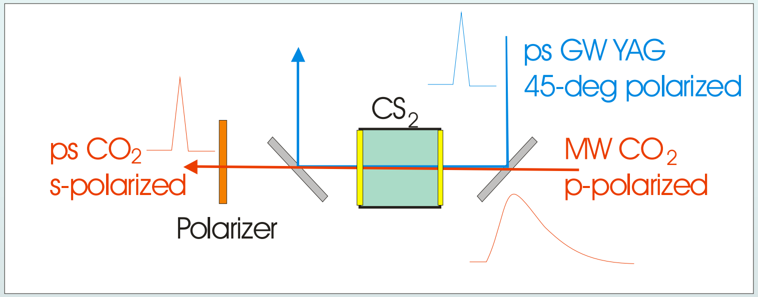
  active liquid (CS_2)

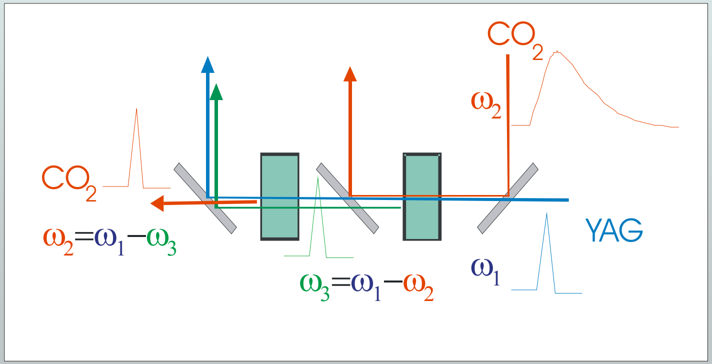
- Differential frequency generation

  in parametric crystals

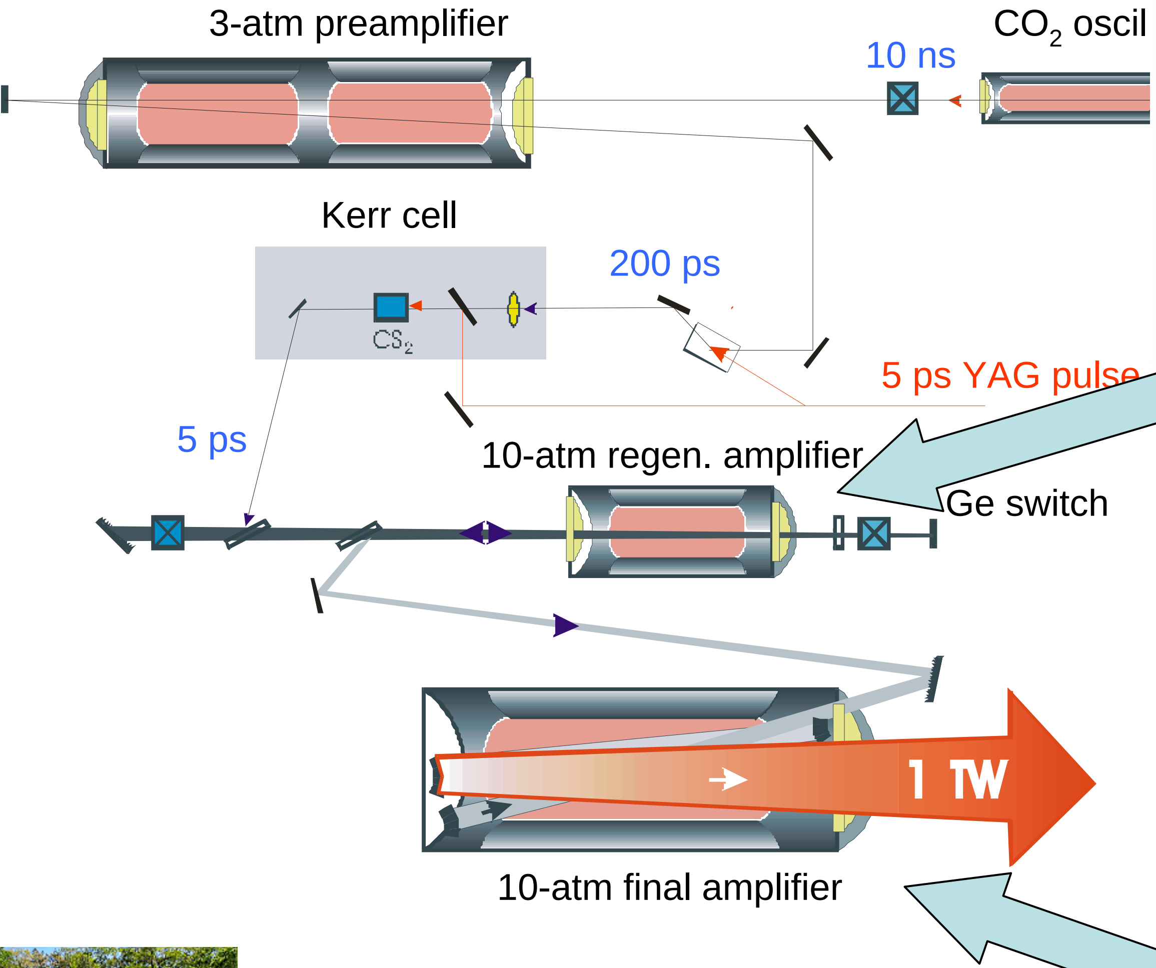


Principle of Semiconductor Optical Switching





BNL/ATF CO_2 laser system delivers 1 TW, 5 ps pulses every 20 seconds


3-atm preamplifier

CO_2 oscil

10 ns

Kerr cell

200 ps

CS_2

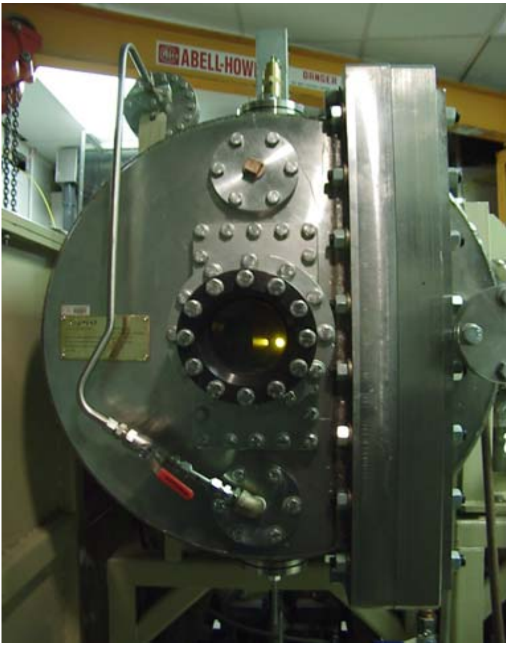
5 ps YAG pulse

5 ps

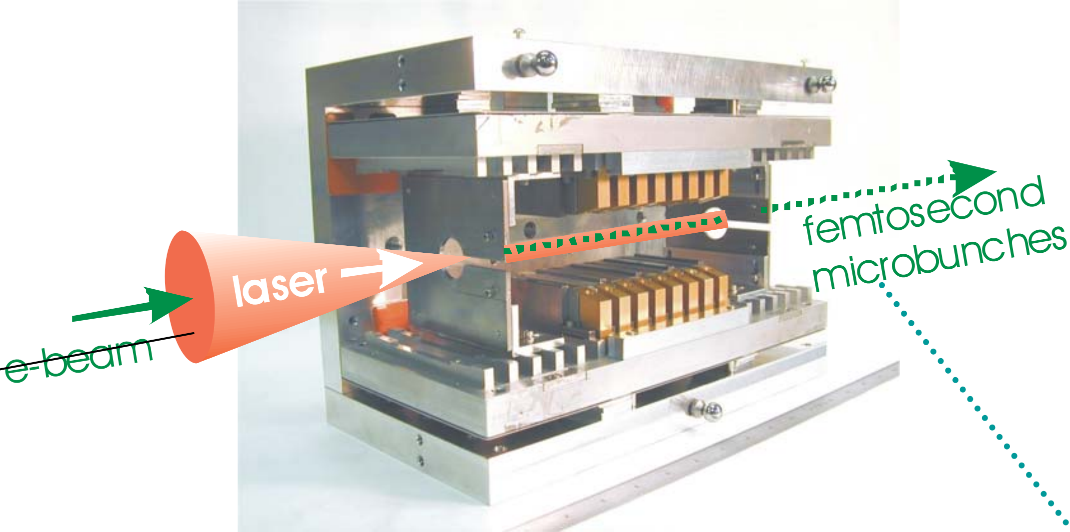
10-atm regen. amplifier

Ge switch

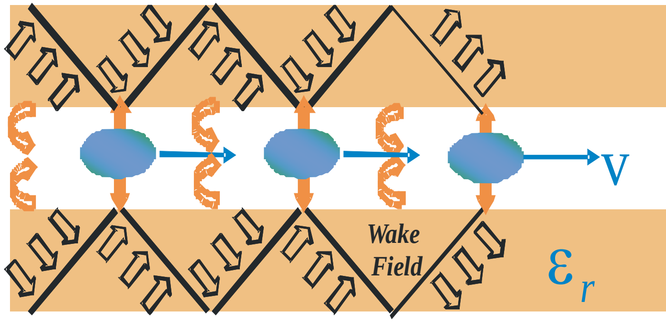
10-atm final amplifier

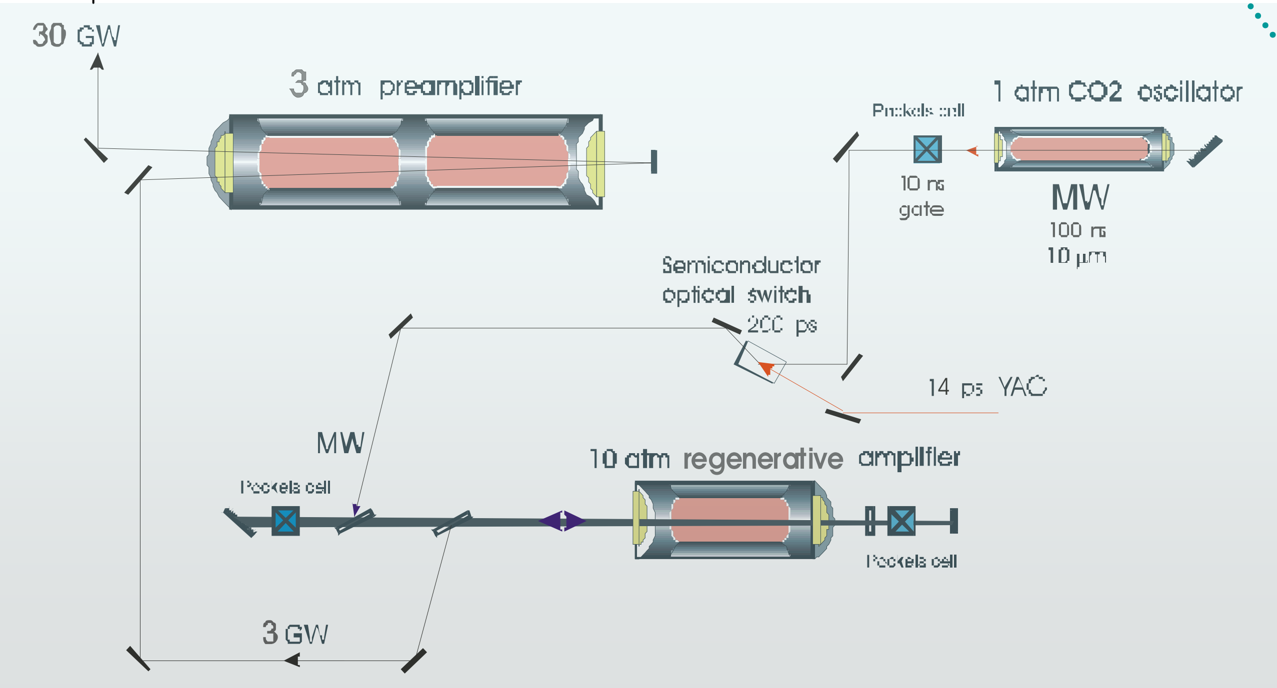


Part of the laser system operates "micro-bunch factory" at 0.3 Hz

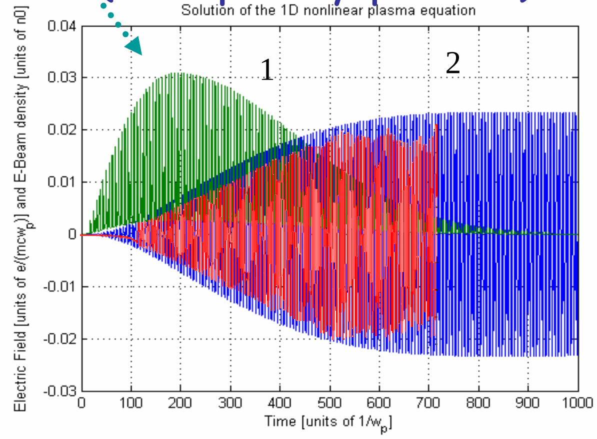


PASER
(in active medium)

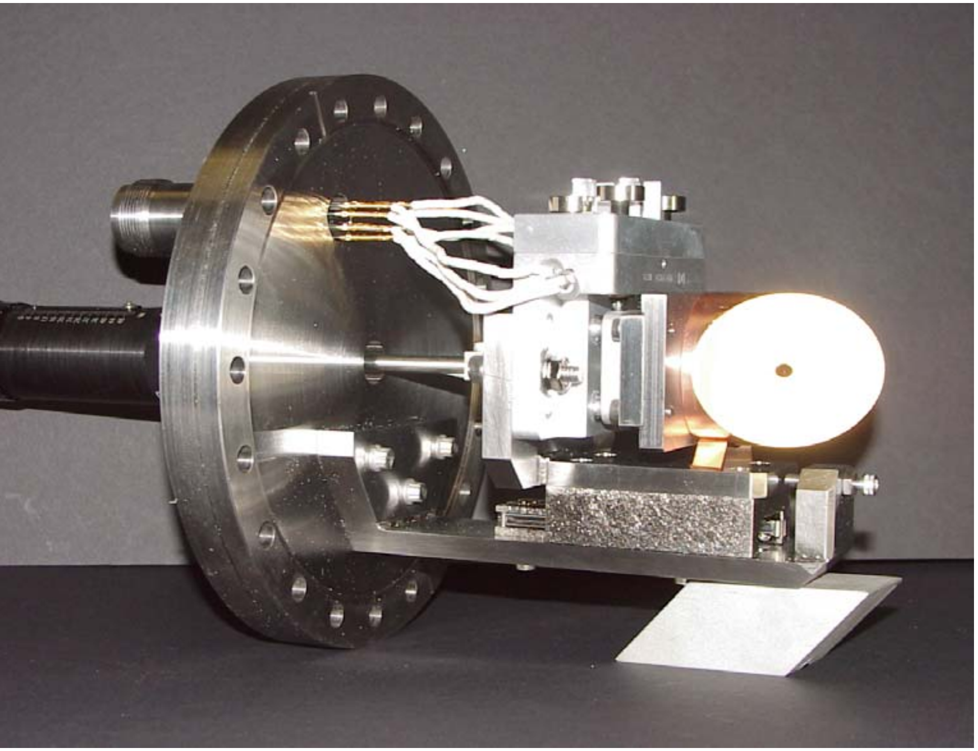




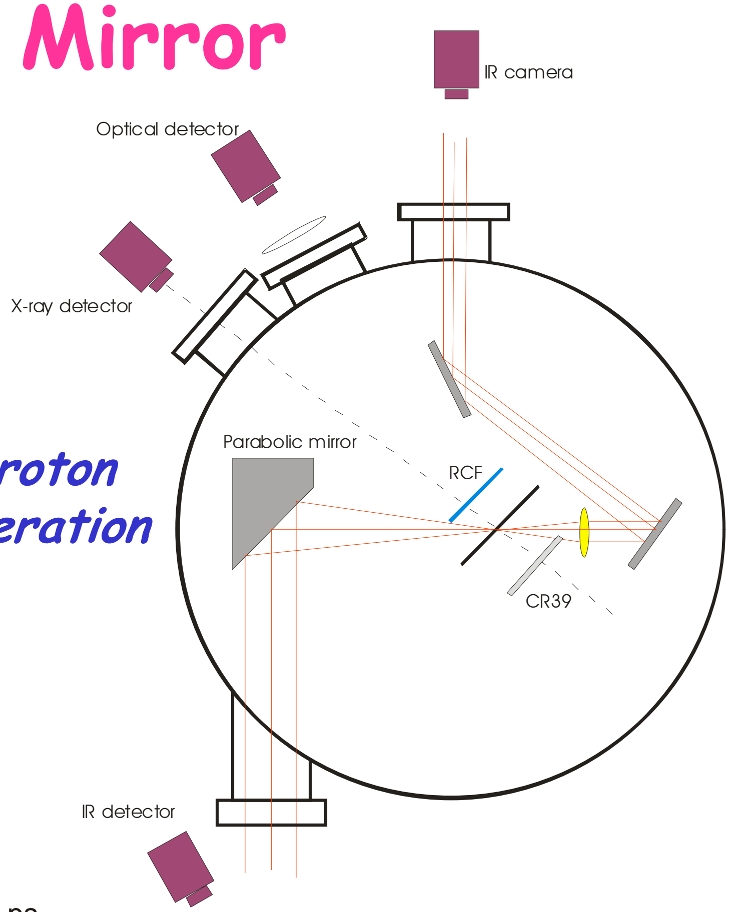
Resonance PWA
(in capillary plasma)



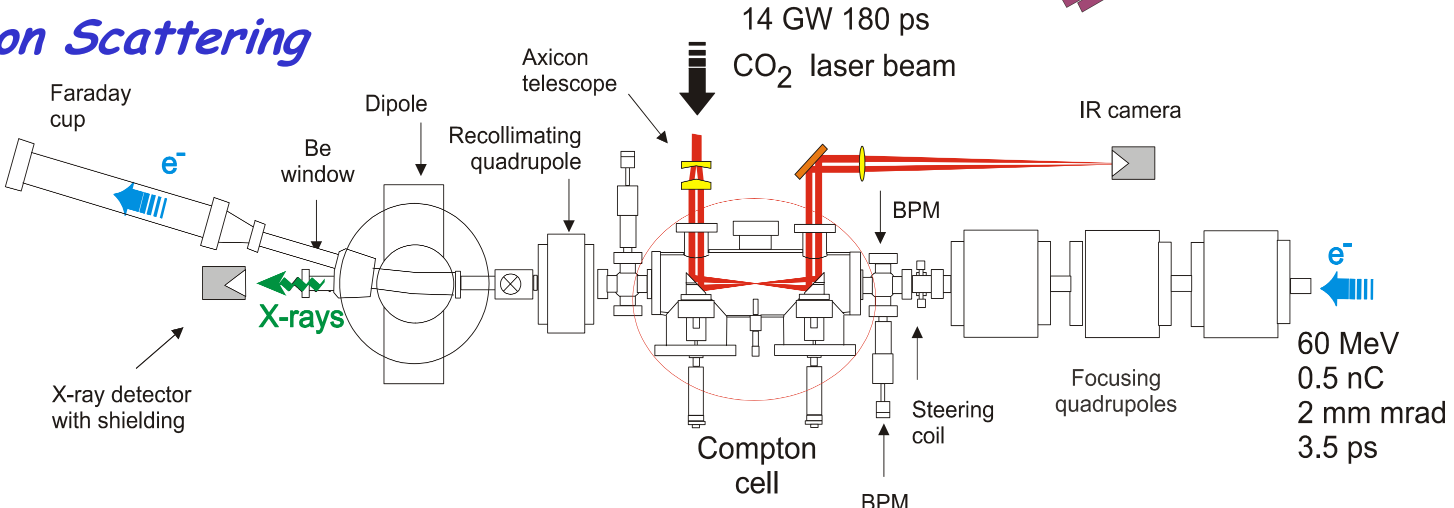
Focusing with Parabolic Mirror



For proton acceleration



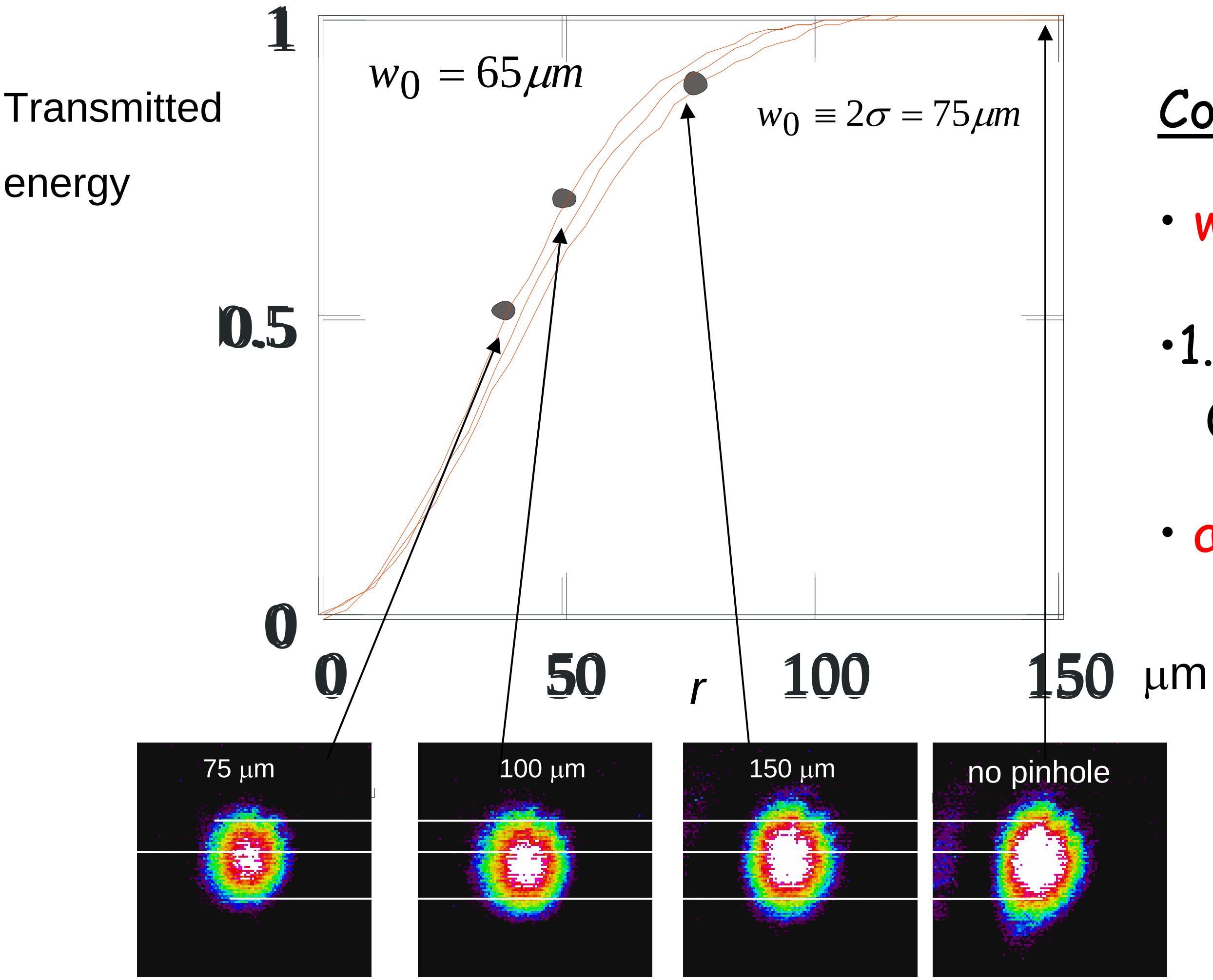
For Compton Scattering



Characterizing the laser focus produced with $f_{\#}=2$ parabola

Gaussian approximation

$$I(r,z) = I_0\left[\frac{w_0}{w(z)}\right]^2 \exp\left[-\frac{2r^2}{w^2(z)}\right]$$



Conclusions:

- w_0=65 μm – best fit
- $1.5\text{x}10^{16}$ W/cm^2 @ 1 TW
- a_0=1 @ λ=10 μm

The importance of condition $a_0=1$ and importance of $\lambda=10\ \mu m$ for reaching this condition:

- Dimensionless laser amplitude

$$a_o=eA/mc^2$$

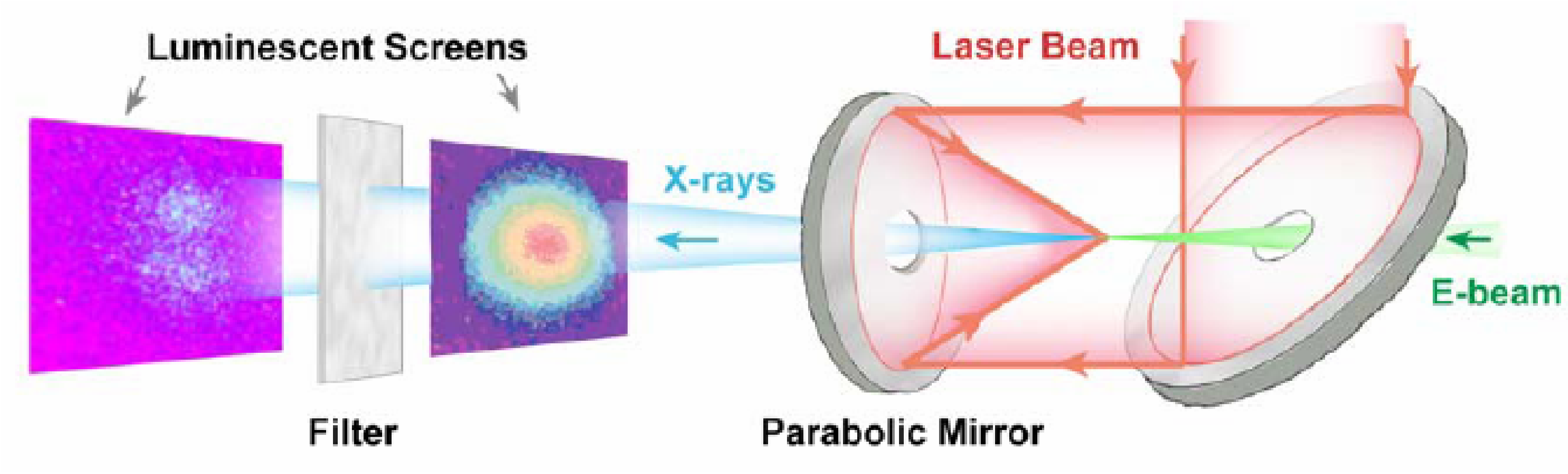
- Electron quiver energy

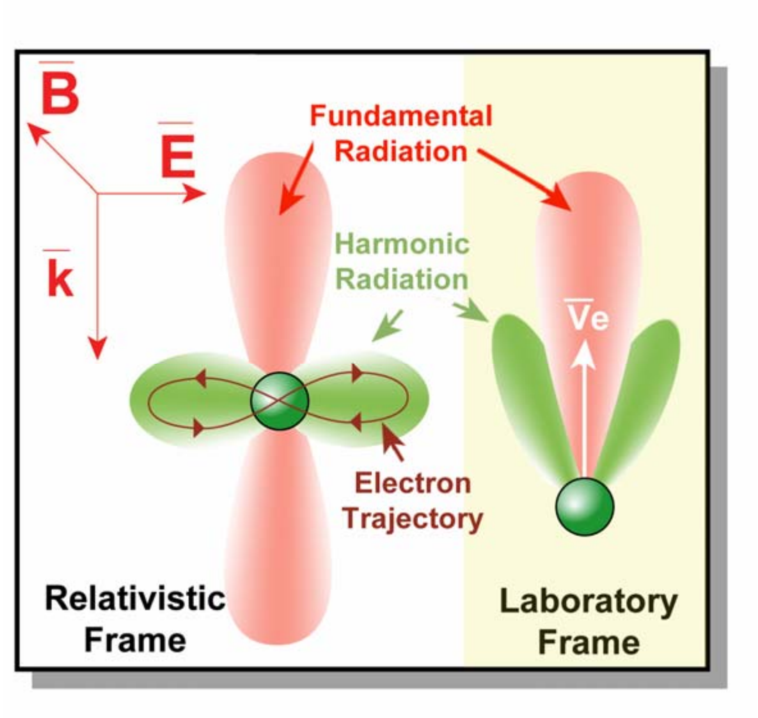
$$E=a_0^2 \times mc^2/2$$

- Electron motion becomes relativistic when

$$a_0=1 \leftrightarrow I\,\lambda^2=1.37\mathrm{x}10^{18}\ \mathrm{W}\ \mu\mathrm{m}^2/\mathrm{cm}^2$$

Proof of attaining $a_0=1$ in ATF experiments:





Nonlinear Compton scattering

Ponderomotive force

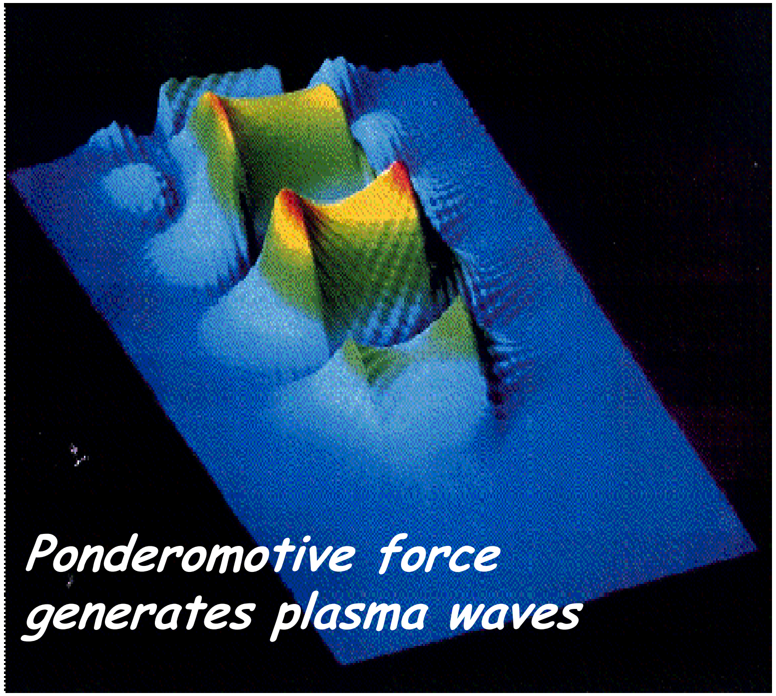
The ponderomotive energy of the electron in the optical field that controls plasma wake generation, ion acceleration and other strong-field phenomena is proportional to **λ^2.**

$$\Phi_{\rm pond} = \frac{1}{4}\frac{e}{m\,\omega^2}\left|\mathbf{E}_0\right|^2.$$

$a_0=1$ when $\Phi_{\rm pond}=mc^2$

$$m\frac{d\mathbf{U}}{dt} = -e\,\nabla\Phi_{\rm pond},$$

An electron experiences a force, called the *ponderomotive force*, which is proportional to the gradient in the amplitude of the wave-field.



Ponderomotive force generates plasma waves

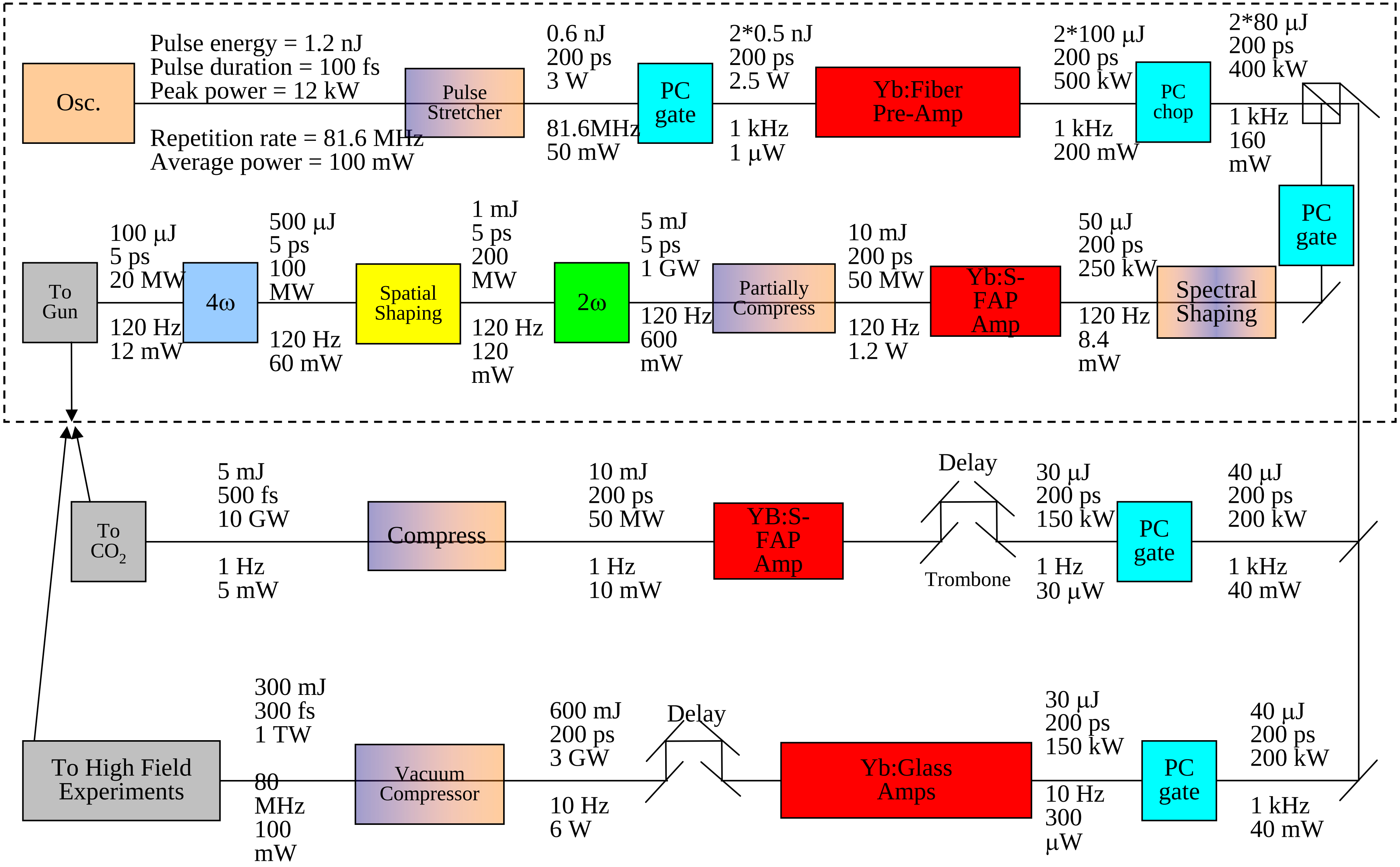
Ion acceleration

Near-term plans for a_0 enhancement will bring ATF laser on line for such popular applications as LWFA or ion acceleration

• Using twice shorter focal length parabola (F=75 mm) gives factor of	x2	a_0~2
• Shortening the pulse length to 1 ps gives another factor of	x2	a_0~2
• Cumulative	x4	a_0~4

•Shortening pulse length has an additional benefit for LWFA as it allows using x25 higher resonance plasma density increasing maximum accelerating gradient proportionally.

Pulse shortening will be achieved with a femtosecond fibre laser



Osc.

Pulse energy = 1.2 nJ
Pulse duration = 100 fs
Peak power = 12 kW
Repetition rate = 81.6 MHz
Average power = 100 mW

Pulse Stretcher

0.6 nJ
200 ps
3 W
81.6MHz
50 mW

PC gate

2*0.5 nJ
200 ps
2.5 W
1 kHz
1 μW

Yb:Fiber Pre-Amp

2*100 μJ
200 ps
500 kW
1 kHz
200 mW

PC chop

2*80 μJ
200 ps
400 kW
1 kHz
160 mW

PC gate

Spectral Shaping

50 μJ
200 ps
250 kW
120 Hz
8.4 mW

Yb:S-FAP Amp

10 mJ
200 ps
50 MW
120 Hz
1.2 W

Partially Compress

5 mJ
5 ps
1 GW
120 Hz
600 mW

2ω

1 mJ
5 ps
200 MW
120 Hz
120 mW

Spatial Shaping

500 μJ
5 ps
100 MW
120 Hz
60 mW

4ω

100 μJ
5 ps
20 MW
120 Hz
12 mW

To Gun

40 μJ
200 ps
200 kW
1 kHz
40 mW

PC gate

30 μJ
200 ps
150 kW
1 Hz
30 μW

Delay
Trombone

YB:S-FAP Amp

10 mJ
200 ps
50 MW
1 Hz
10 mW

Compress

5 mJ
500 fs
10 GW
1 Hz
5 mW

To CO_2

40 μJ
200 ps
200 kW
1 kHz
40 mW

PC gate

30 μJ
200 ps
150 kW
10 Hz
300 μW

Yb:Glass Amps

Delay

600 mJ
200 ps
3 GW
10 Hz
6 W

Vacuum Compressor

300 mJ
300 fs
1 TW
80 MHz
100 mW

To High Field Experiments

Directions for ultra-fast CO_2 laser improvement:

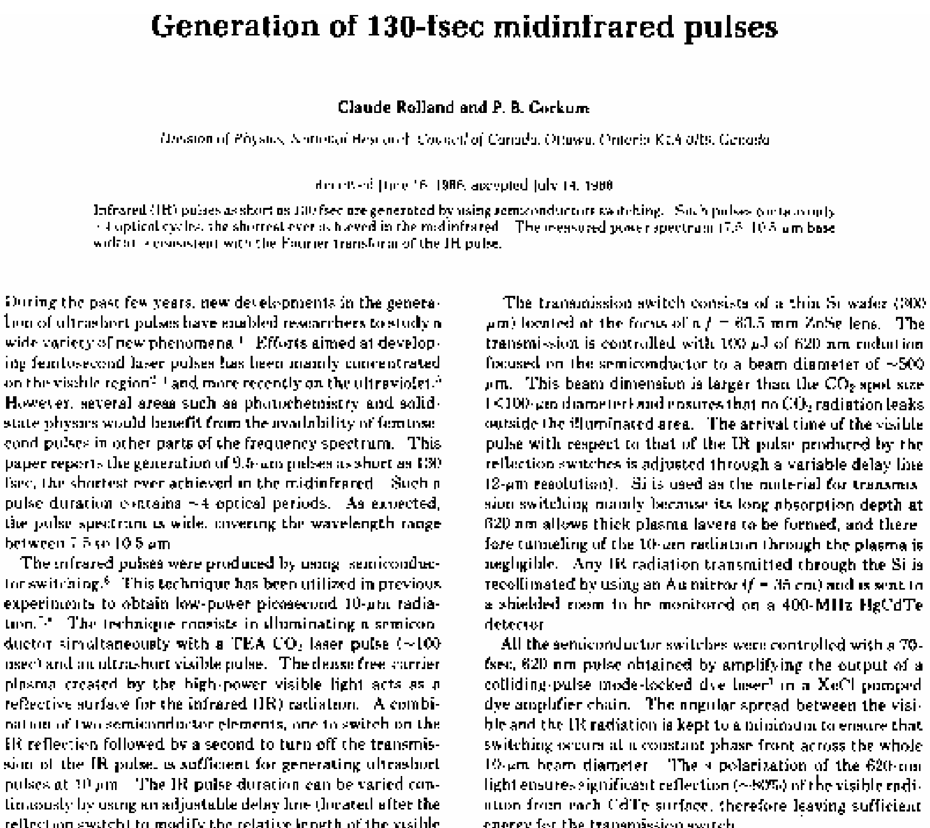
- Femtosecond pulses (few cycles)
- Higher energy per pulse
- Higher repetition rate
- Higher average power

CO_2 femtosecond pulse generation and amplification

- Ultra-fast slicing
- Amplification in multi-isotope mixture
- Pulse chirping and dispersive compression
- Raman backscattering
- Power broadening

Ultra-fast slicing and amplification in multi-isotope mixture

Paul Corkum demonstrated in 1986 semiconductor slicing of 130 fs CO_2 pulses



Generation of 130-fsec midinfrared pulses

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Received June 16, 1986; accepted July 14, 1986

Infrared (IR) pulses as short as 130 fsec are generated by using semiconductor switching. Such pulses contain only ~4 optical cycles, the shortest ever achieved in the midinfrared. The measured power spectrum (7.5–10.5 µm base width) is consistent with the Fourier transform of the IR pulse.

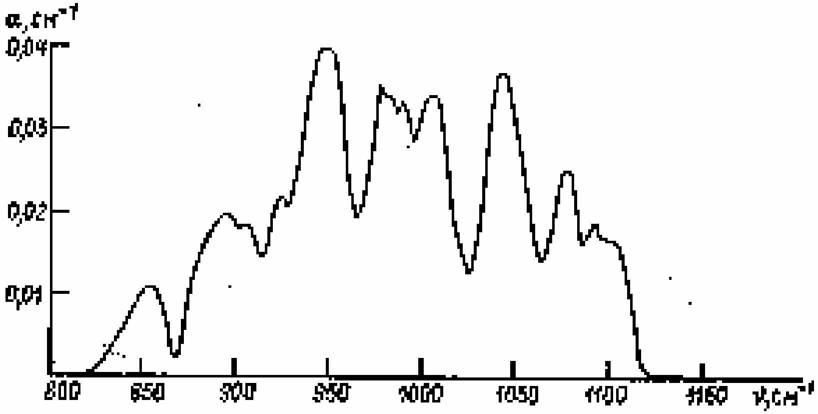
During the past few years, new developments in the generation of ultrashort pulses have enabled researchers to study a wide variety of new phenomena.[1] Efforts aimed at developing femtosecond laser pulses has been mainly concentrated on the visible region[2,3] and more recently on the ultraviolet.[4] However, several areas such as photochemistry and solid-state physics would benefit from the availability of femtosecond pulses in other parts of the frequency spectrum. This paper reports the generation of 9.5-µm pulses as short as 130 fsec, the shortest ever achieved in the midinfrared. Such a pulse duration contains ~4 optical periods. As expected, the pulse spectrum is wide, covering the wavelength range between 7.5 to 10.5 µm.

The infrared pulses were produced by using semiconductor switching.[5] This technique has been utilized in previous experiments to obtain low-power picosecond 10-µm radiation.[6-8] The technique consists in illuminating a semiconductor simultaneously with a TEA CO_2 laser pulse (~100 nsec) and an ultrashort visible pulse. The dense free carrier plasma created by the high-power visible light acts as a reflective surface for the infrared (IR) radiation. A combination of two semiconductor elements, one to switch on the IR reflection followed by a second to turn off the transmission of the IR pulse, is sufficient for generating ultrashort pulses at 10 µm. The IR pulse duration can be varied continuously by using an adjustable delay line (located after the reflection switch) to modify the relative length of the visible

The transmission switch consists of a thin Si wafer (300 µm) located at the focus of a $f = 63.5$ mm ZnSe lens. The transmission is controlled with 100 µJ of 620 nm radiation focused on the semiconductor to a beam diameter of ~500 µm. This beam dimension is larger than the CO_2 spot size (<100-µm diameter) and ensures that no CO_2 radiation leaks outside the illuminated area. The arrival time of the visible pulse with respect to that of the IR pulse produced by the reflection switches is adjusted through a variable delay line (2-µm resolution). Si is used as the material for transmission switching mainly because its long absorption depth at 620 nm allows thick plasma layers to be formed, and therefore tunneling of the 10-µm radiation through the plasma is negligible. Any IR radiation transmitted through the Si is recollimated by using an Au mirror ($f = 35$ cm) and is sent to a shielded room to be monitored on a 400-MHz HgCdTe detector.

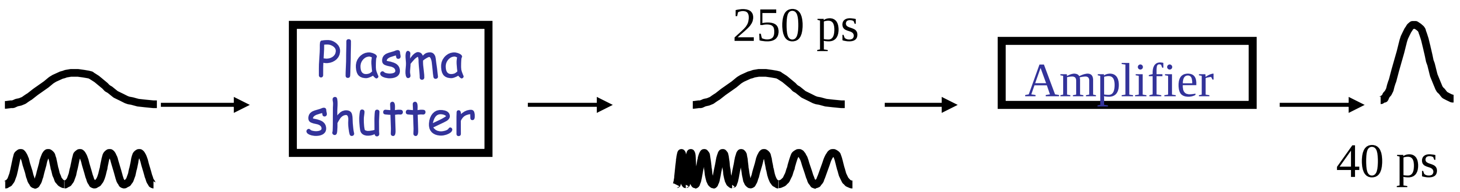
All the semiconductor switches were controlled with a 70-fsec, 620 nm pulse obtained by amplifying the output of a colliding-pulse mode-locked dye laser[1] in a XeCl pumped dye amplifier chain. The angular spread between the visible and the IR radiation is kept to a minimum to ensure that switching occurs at a constant phase front across the whole 10-µm beam diameter. The s polarization of the 620-nm light ensures significant reflection (~80%) of the visible radiation from each CdTe surface, therefore leaving sufficient energy for the transmission switch.

Direct amplification in a 4-atm CO_2 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.



UCLA

Pulse Chirping and Compression

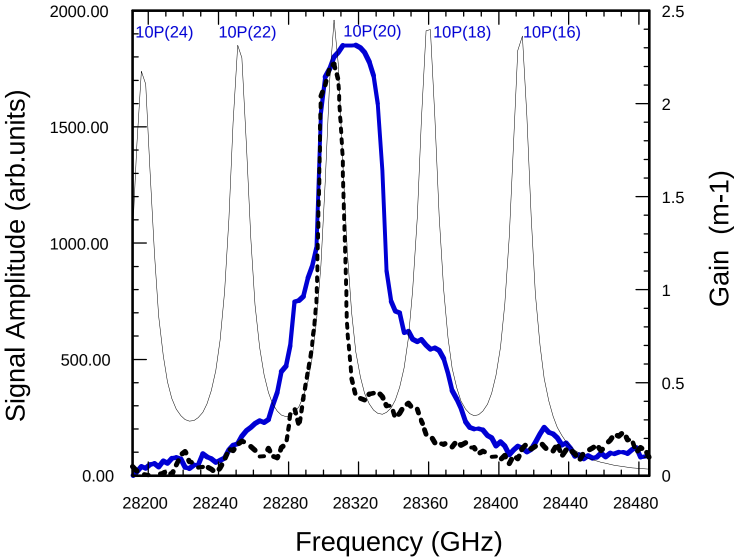


250 ps

Plasma shutter

Amplifier

40 ps



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

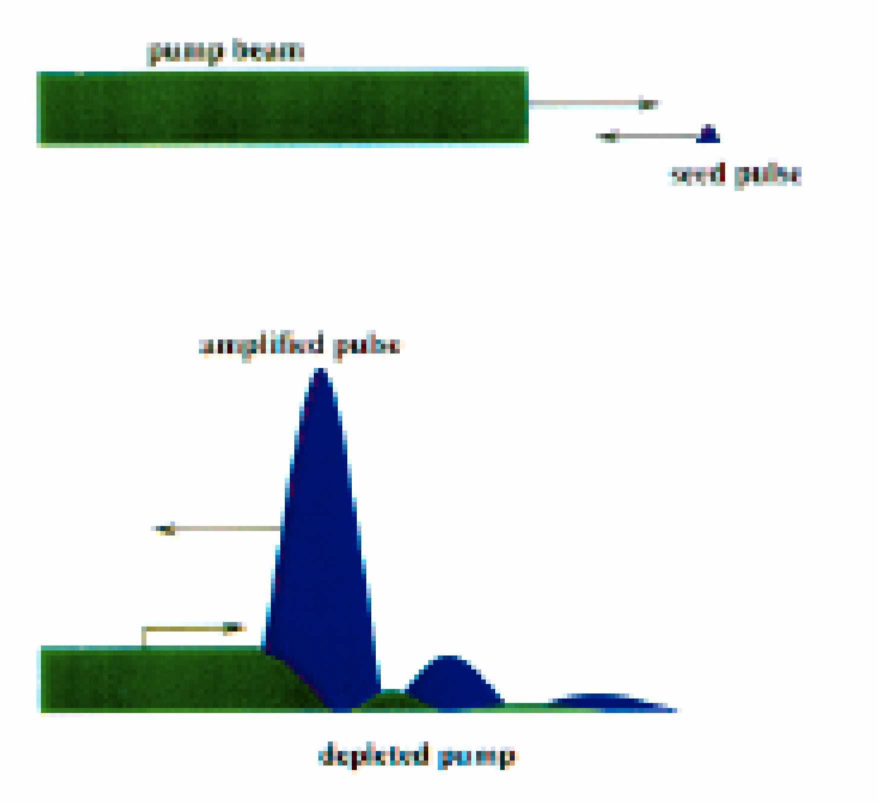
$$\eta(x,t)=\sqrt{1-n_e(x,t)/n_{cr}}$$

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

Measured blue shift 40 GHz corresponds to $n_e = 3\times10^{17}\text{cm}^{-3}$

Can be used to compress 1 ps to 100 fs In dispersive optical element such as ZnSe window

Raman backscattering



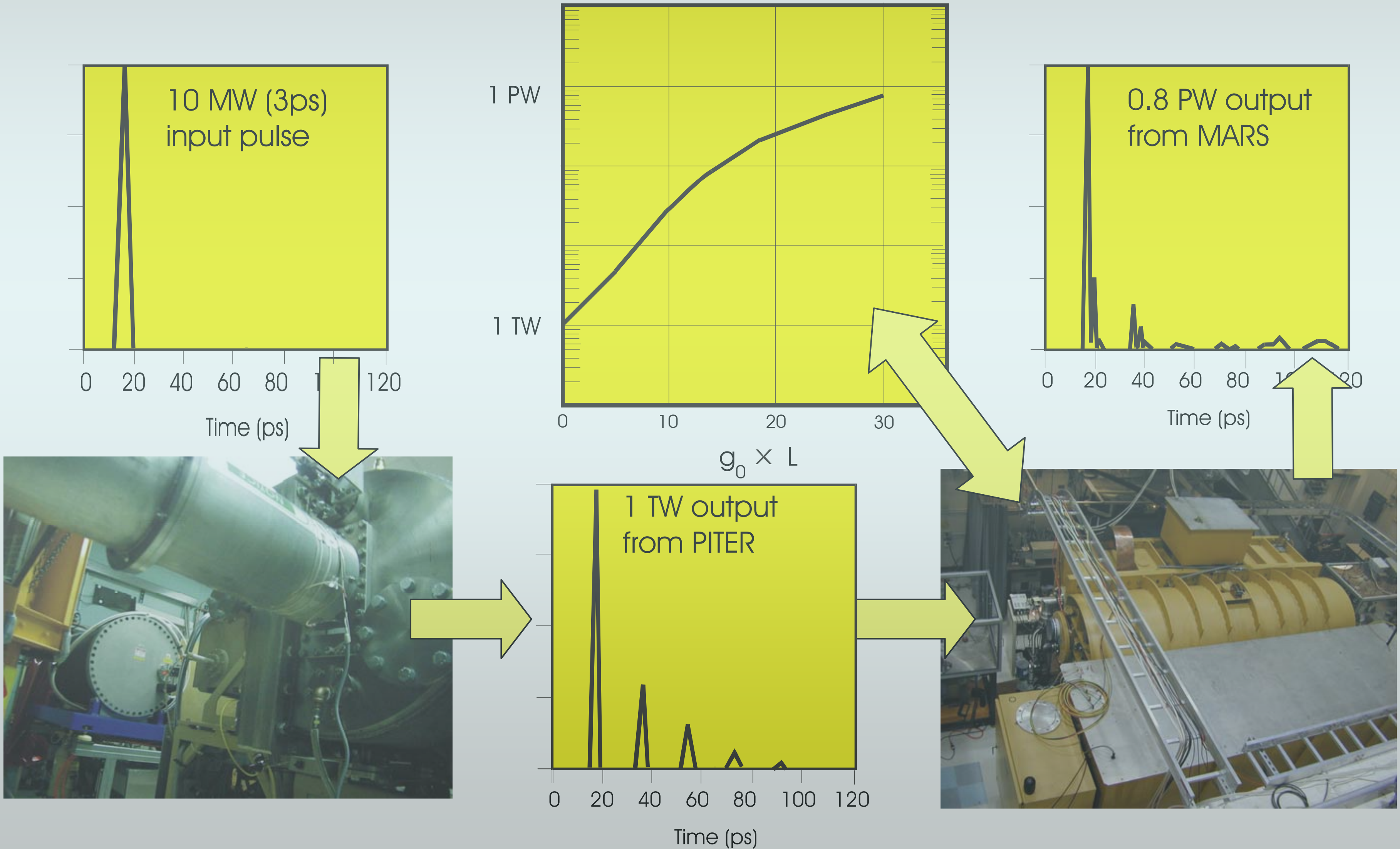
Raman backscattering of a 9.6-μm nanosecond pump into the counter-propagating femtosecond 10.6-μm seed pulse in a resonance plasma $\omega_p=\Delta\omega$.

Proposed by G. Shvets

Hypothetical combination of PITER-I with MARS (UCLA) provides Petawatt capability @ 1 ps

Use **power or Stark broadening** in laser field

$\Delta \nu_R = \mu E / \hbar$, at 10^{10} W/cm^2 $\Delta \nu_R = 37 GHz$



CCLRC

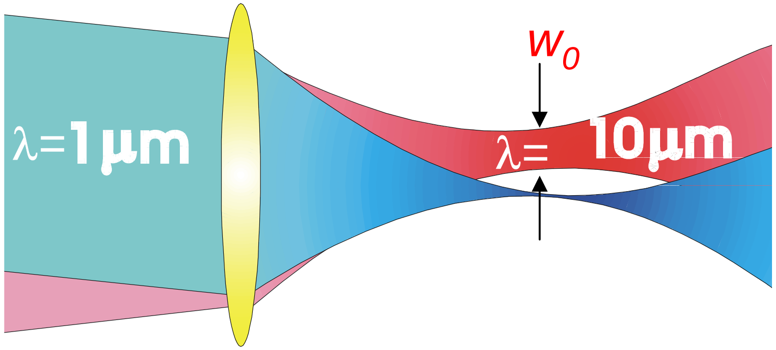
Rutherford Appleton Laboratory's

Central Laser Facility

Nd:glass Petawatt VULCAN laser

$I=10^{20}$ W/cm^{2}; $a_0 \sim 10$

…but λ=1 μm permits tighter focusing (assuming $w_0 \sim \lambda$) !



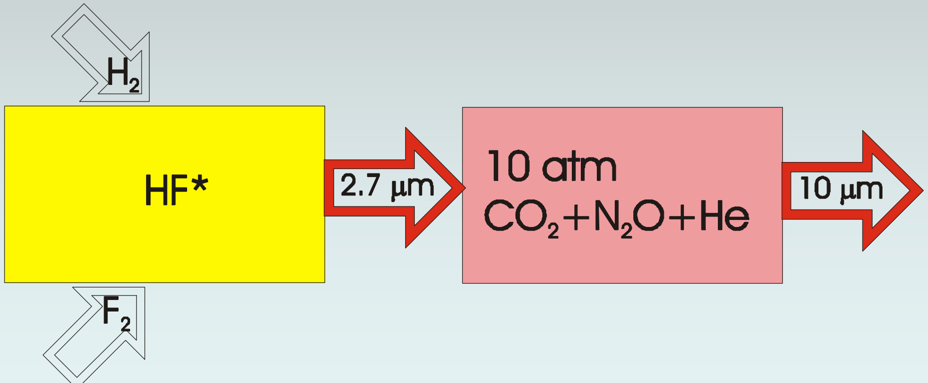
However:

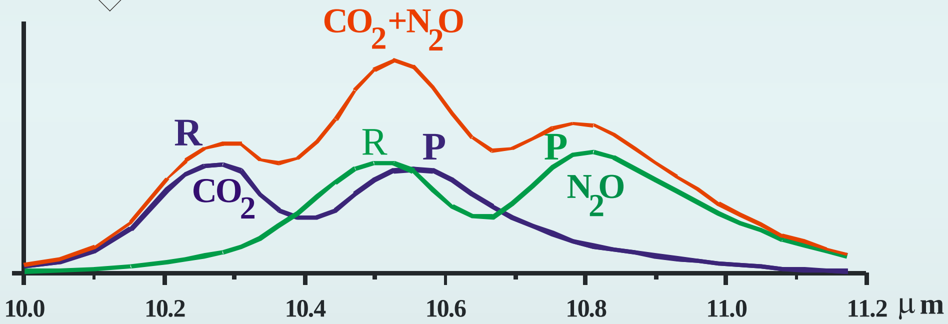
- ♦ <u>Interacting with e-beam</u> you do not want to focus laser tighter than e-beam (decreases acceleration quality and x-ray yield). CO_2 laser focusing is sufficient to interact with low-emittance e-beams.

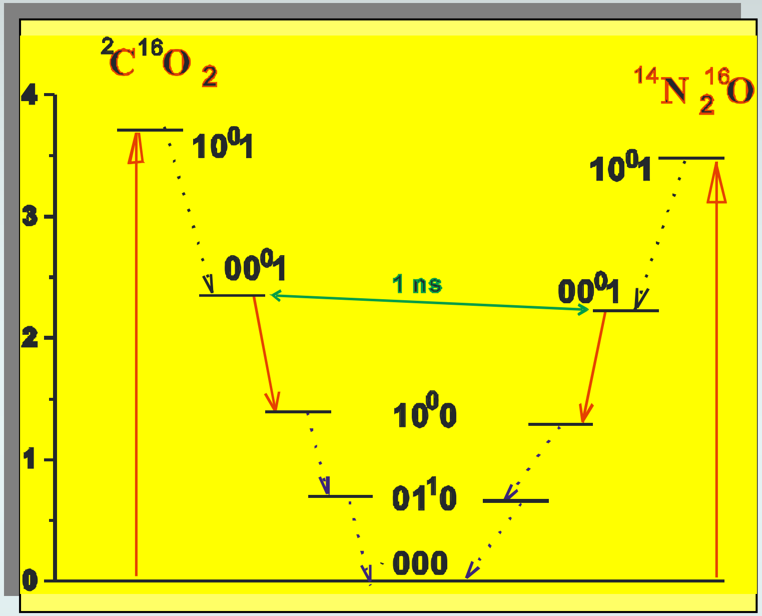
- ♦ <u>In laser/matter interactions</u> ten times tighter focus of the 1 μm laser results in 100 times smaller area and 1000 times smaller interaction volume where we can see an equivalent effect. This will proportionally reduce the process yield.

- ♦ Thus, 1 PW CO_2 laser in certain cases is equivalent to 100 PW solid state laser!

High-pressure CO_2:N_2O laser optically pumped by HF chemical laser





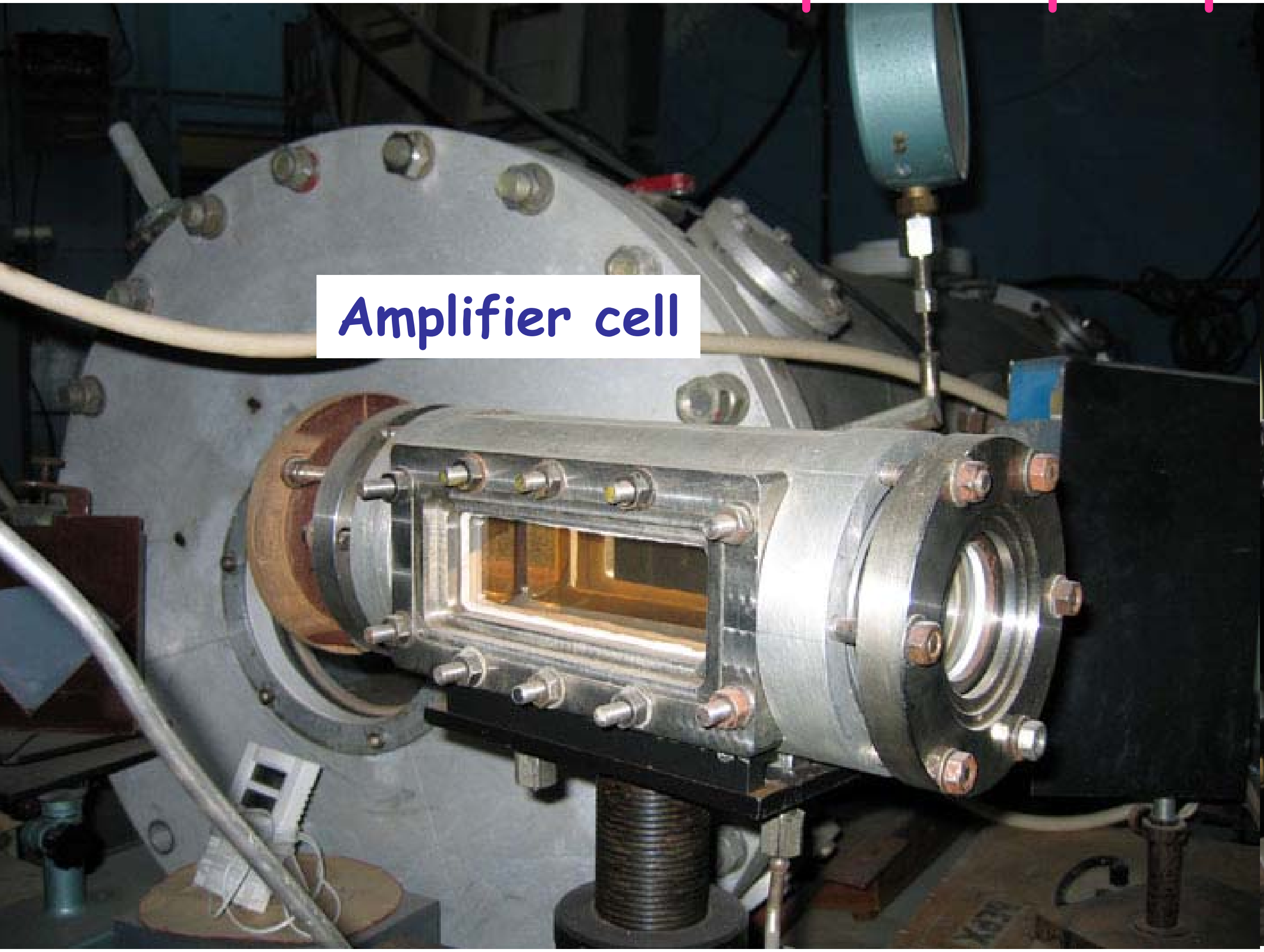


Demonstrated: Pumping Efficiency 20%, SSG 10%/cm

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

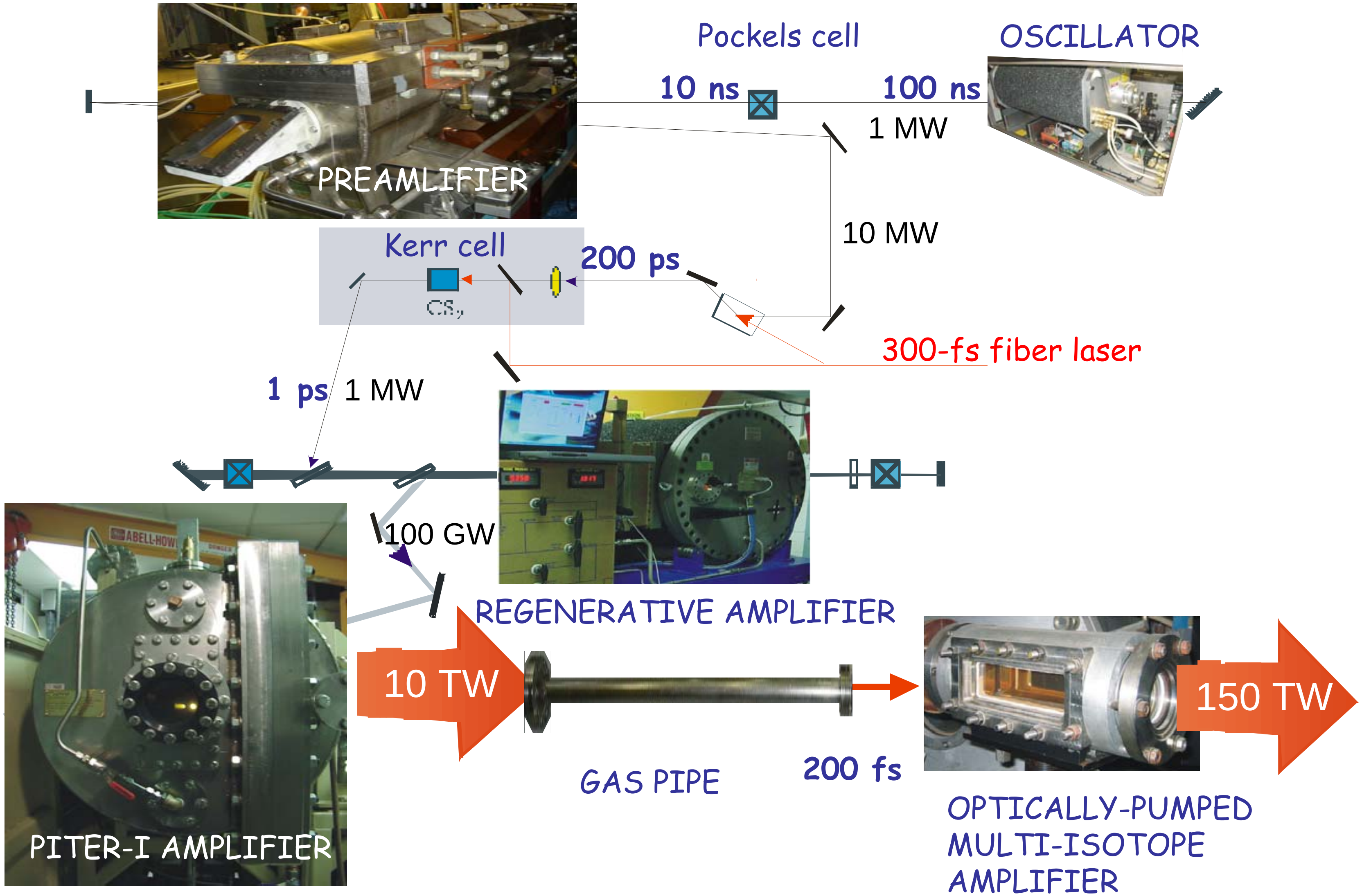
High-pressure CO_2 laser amplifier with optical pumping



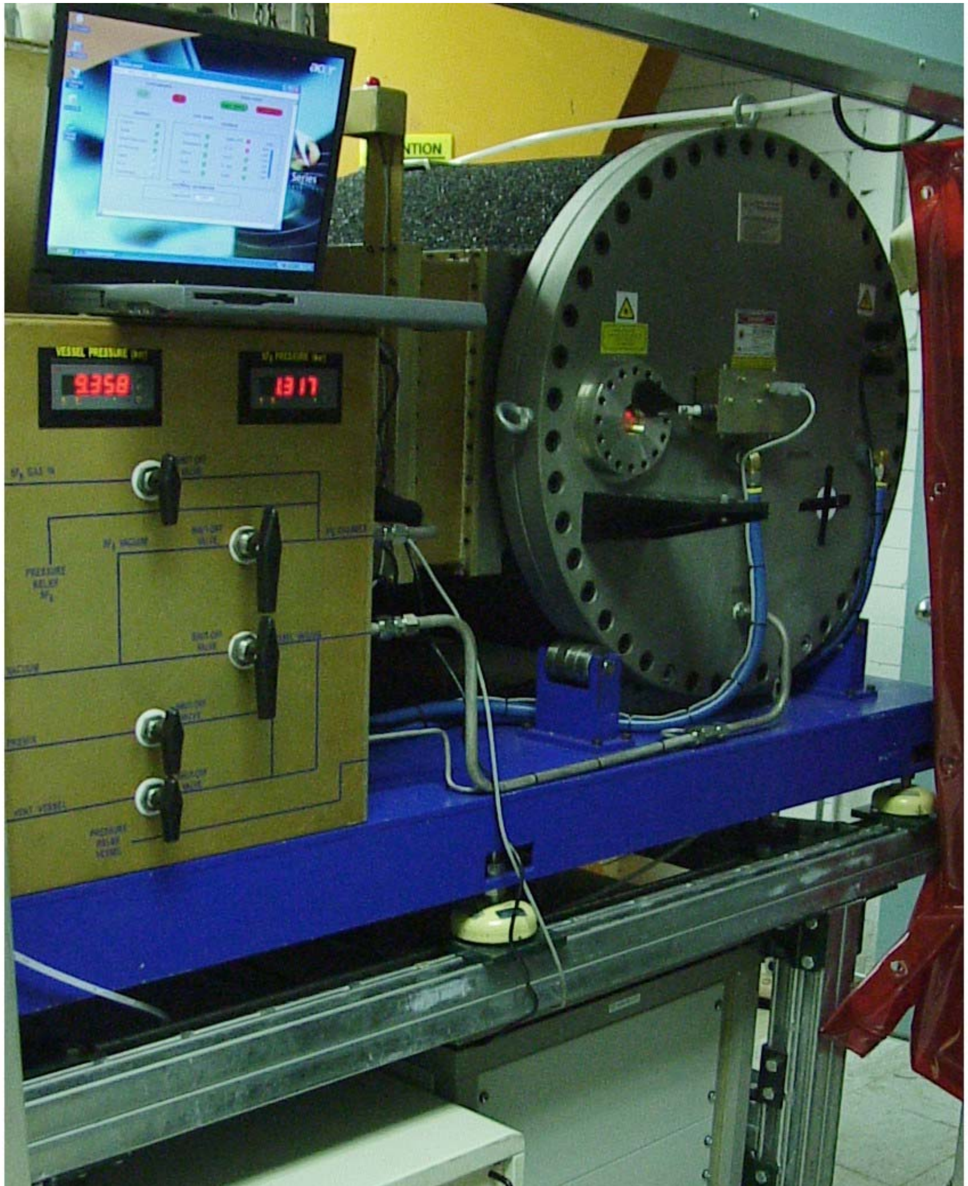
Courtesy of M. Azarov
Russian Academy of Science

Capabilities of compact 1.4 liter optically pumped high-pressure CO_2 amplifier:
- Output energy: 30J/pulse
- Repetition rate: >10 Hz (limited by a pump laser)
- Many ATF laser components are compatible to this speed

200 fs, 150 TW can be achieved at ATF;
this allows a_0=10, potentially at linac's repetition rate

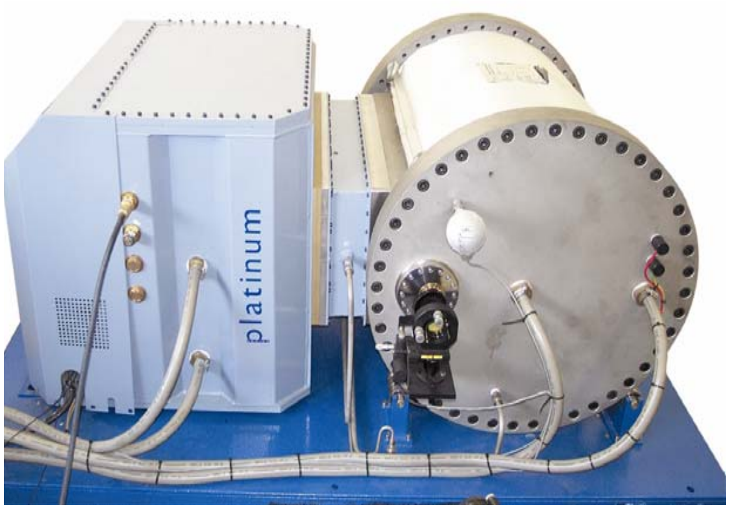


Commercially Available High-Pressure High Repetition-Rate CO_2 Lasers



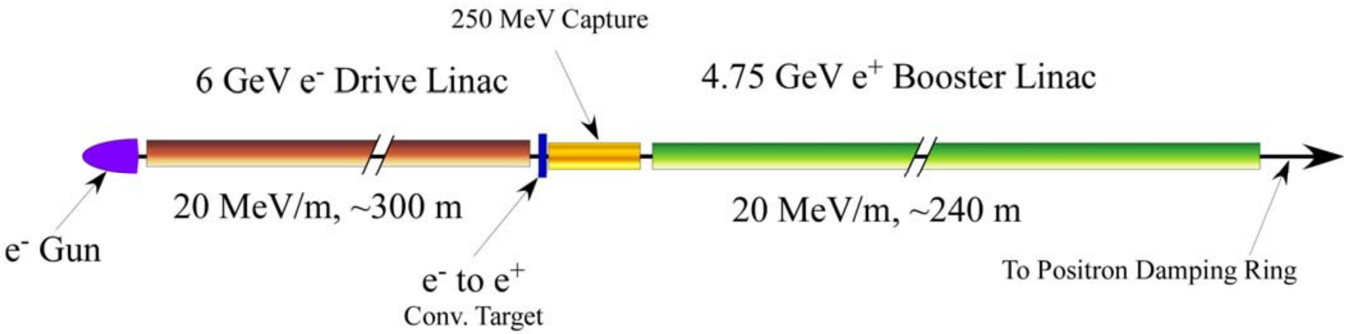
SCIENTIFIC DEVELOPMENT & INTEGRATION (PTY) LTD

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

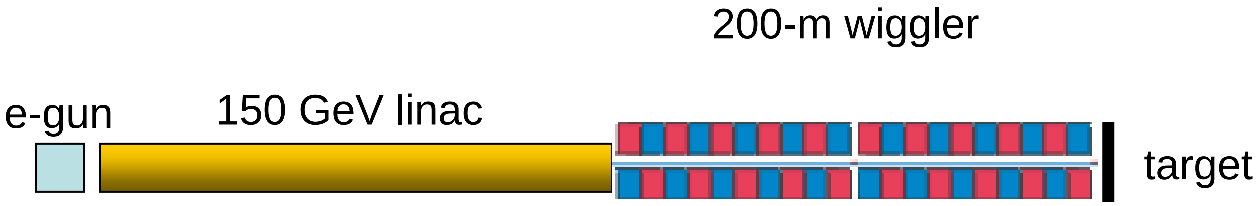


Current Positron Source Proposals for ILC

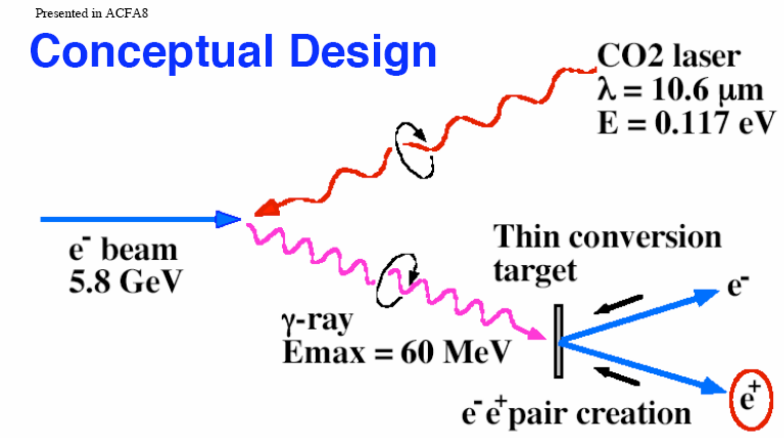
Conventional non-polarized positron source



Polarized gamma source by spontaneous wiggler radiation



Polarized gamma source by Compton scattering

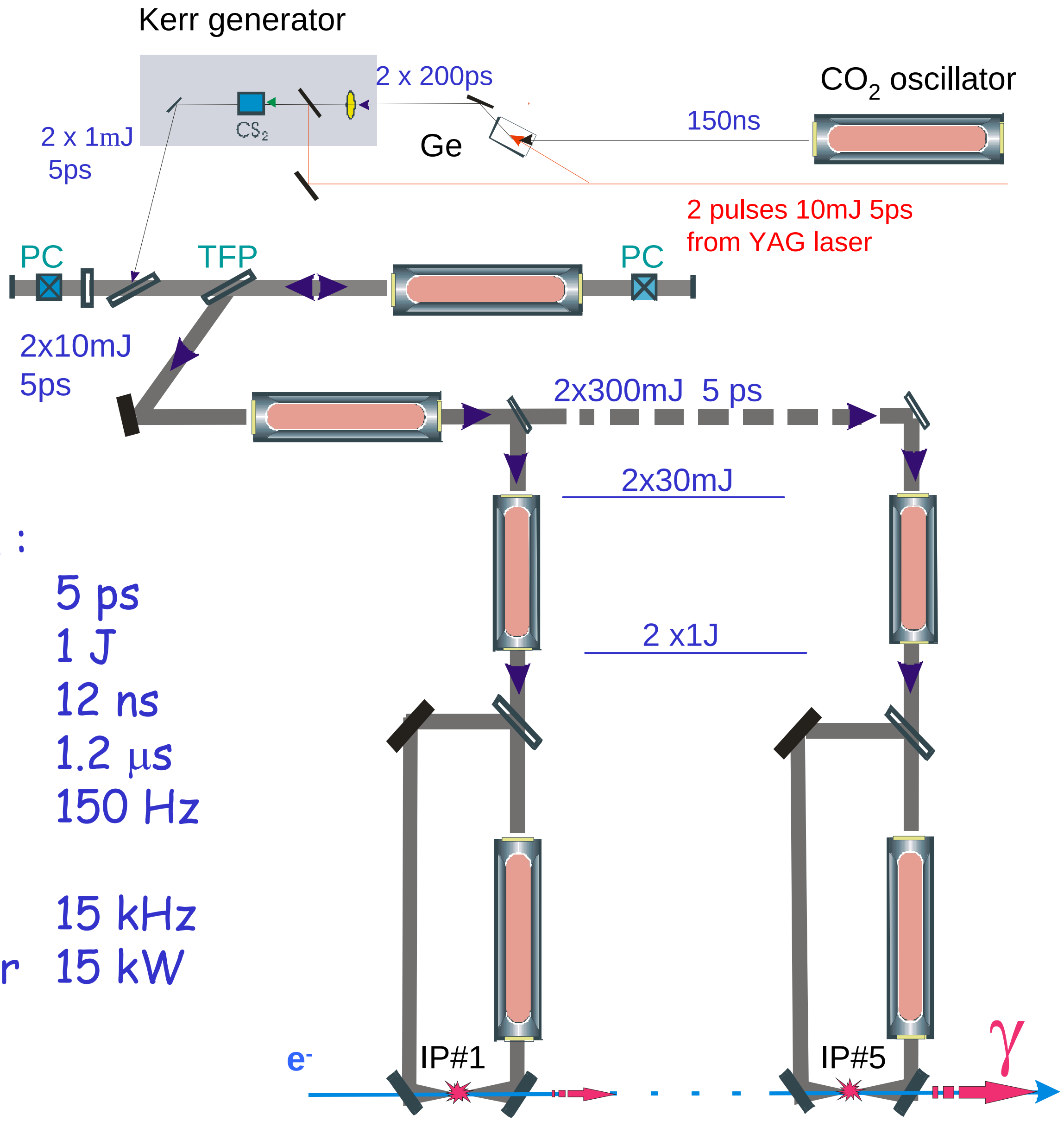


Polarized γ source requirements

Parameter	**Symbol**	**Value**	**Unit**
Pulse repetition rate	f_{rep}	150	Hz
Bunches per pulse	N_b	100	
Bunch Spacing	Δt_b	12	ns
Laser energy	E_{laser}	1	J
Size at focus	σ_{laser}	40	μm
Laser pulse length	t_{laser}	5	ps
Number of γ per electron	N_γ / n_e	1	
e^- per bunch	n_e	6×10^{11}	
Number of lasers	N_{laser}	10	
Number of γ per bunch	$N_\gamma \times N_{laser}$	6×10^{12}	

Needed: 15 kHz, 15kW, picosecond,
sub-terawatt CO_2 laser

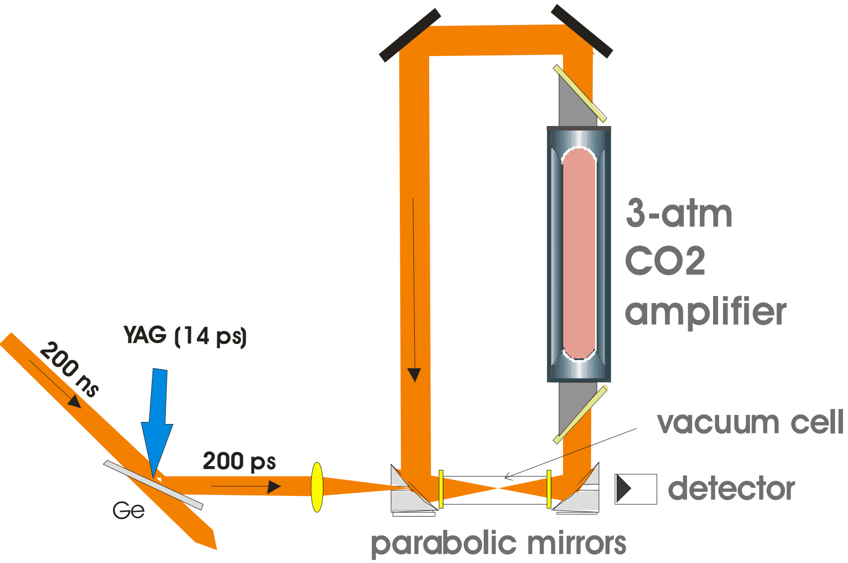
CO_2 Laser system for ILC PPS

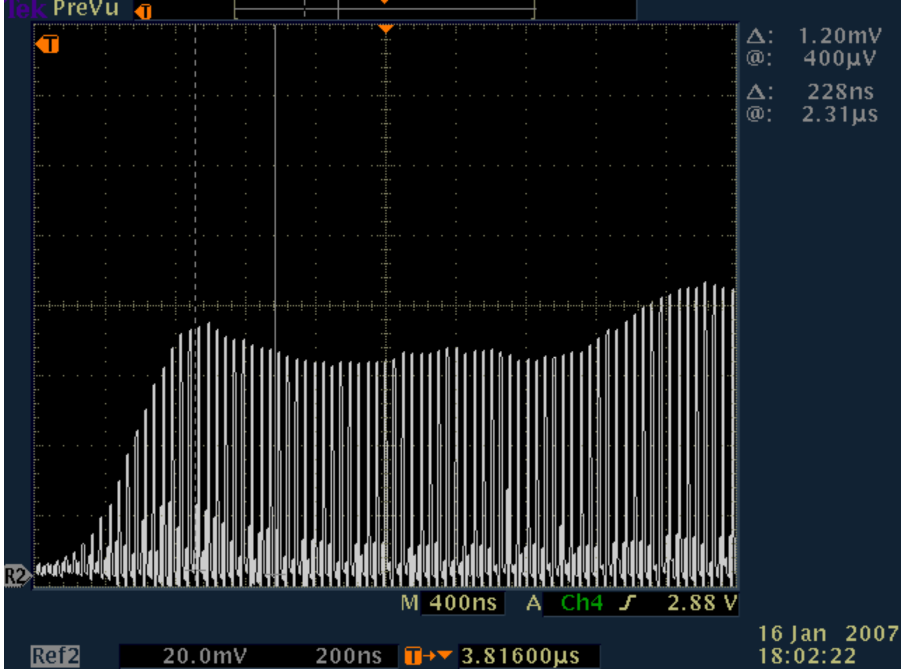


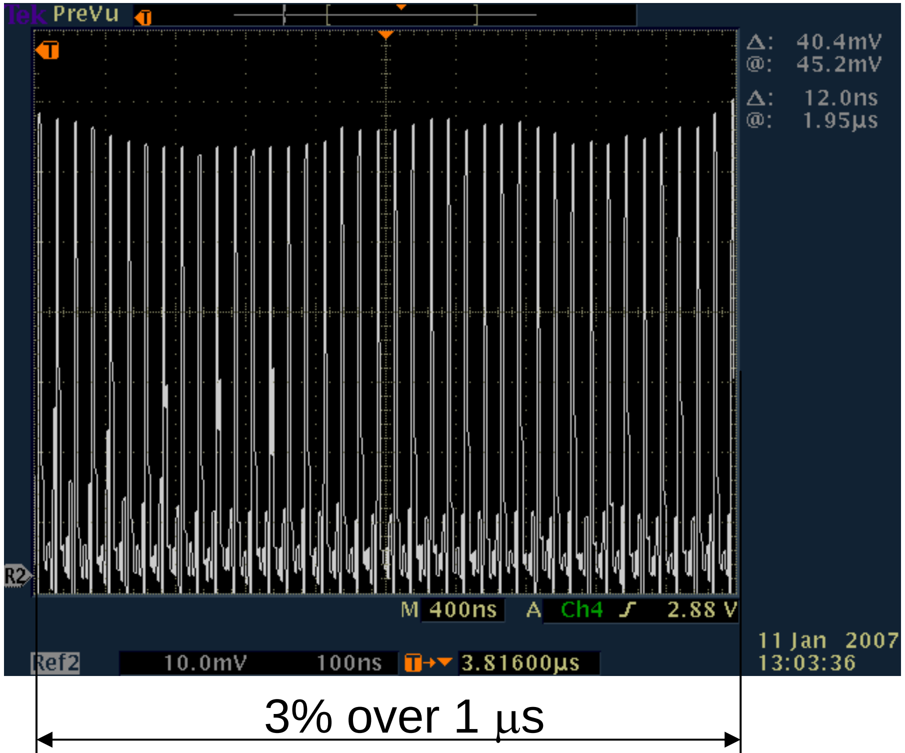
intra-cavity pulse circulation :

– pulse length	5 ps
– energy per pulse	1 J
– period inside pulse train	12 ns
– total train duration	1.2 µs
– train repetition rate	150 Hz
– Cumulative rep. rate	15 kHz
– Cumulative average power	15 kW

Test setup







Observations:

- Optical gain over 4 µs
- Single seed pulse amplification continues to the end

Conclusions

- CO_2 laser offers fundamental advantages due to the λ^2-proportional ponderomotive potential and λ-proportional number of photons per 1J.
- 5-ps, 5-J, 1-TW CO_2 laser has been demonstrated and used in ATF user's experiments.
- Demonstration of a_0~1 in nonlinear Compton scattering and ion acceleration experiments.
- Near-term possibilities for a_0~4 by tighter focusing and shortening to 1 ps with a new fiber laser.
- Available resources for 200 fs CO_2 pulse generation and amplification: ultra-fast slicing and amplification in multi-isotope mixture; pulse chirping and dispersive compression; Raman backscattering.
- Power broadening allows to reach petawatt power in a big medium-pressure CO_2 amplifier such as UCLA MARS.
- Multi-terawatt, femtosecond CO_2 laser with optical pumping can operate at the linac's and higher repetition rate.
- Commercially available high-pressure CO_2 lasers can provide 1 TW output at up to 500Hz and 0.75 kW average power.
- Non-destructive intra-cavity process, such as Compton scattering, allows to utilize a terawatt laser beam more efficiently at multi-kHz rate and >10 kW average power (potential application for ILC).