Multi-pass CO_2 laser cavity for high repetition pulse trains

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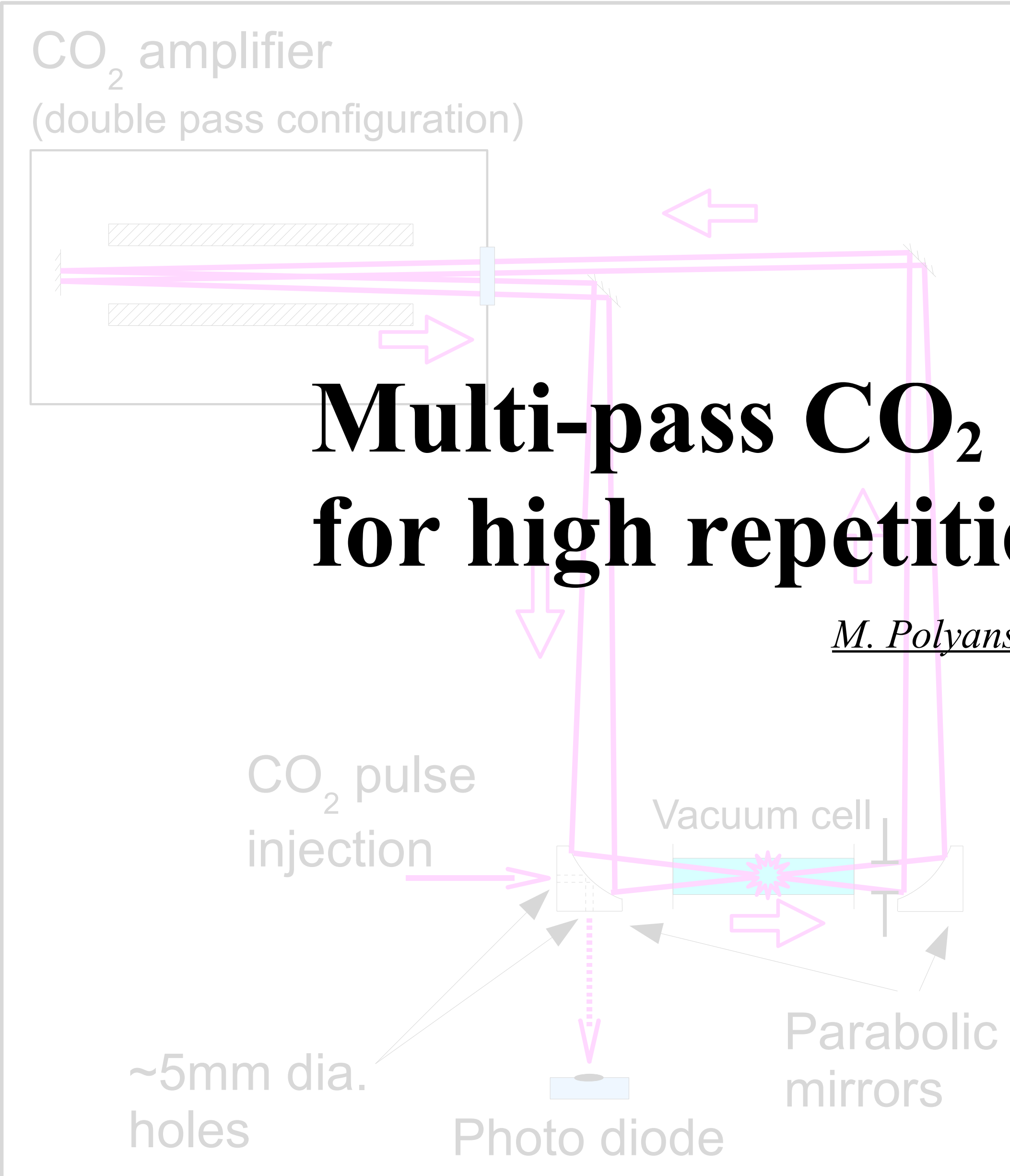
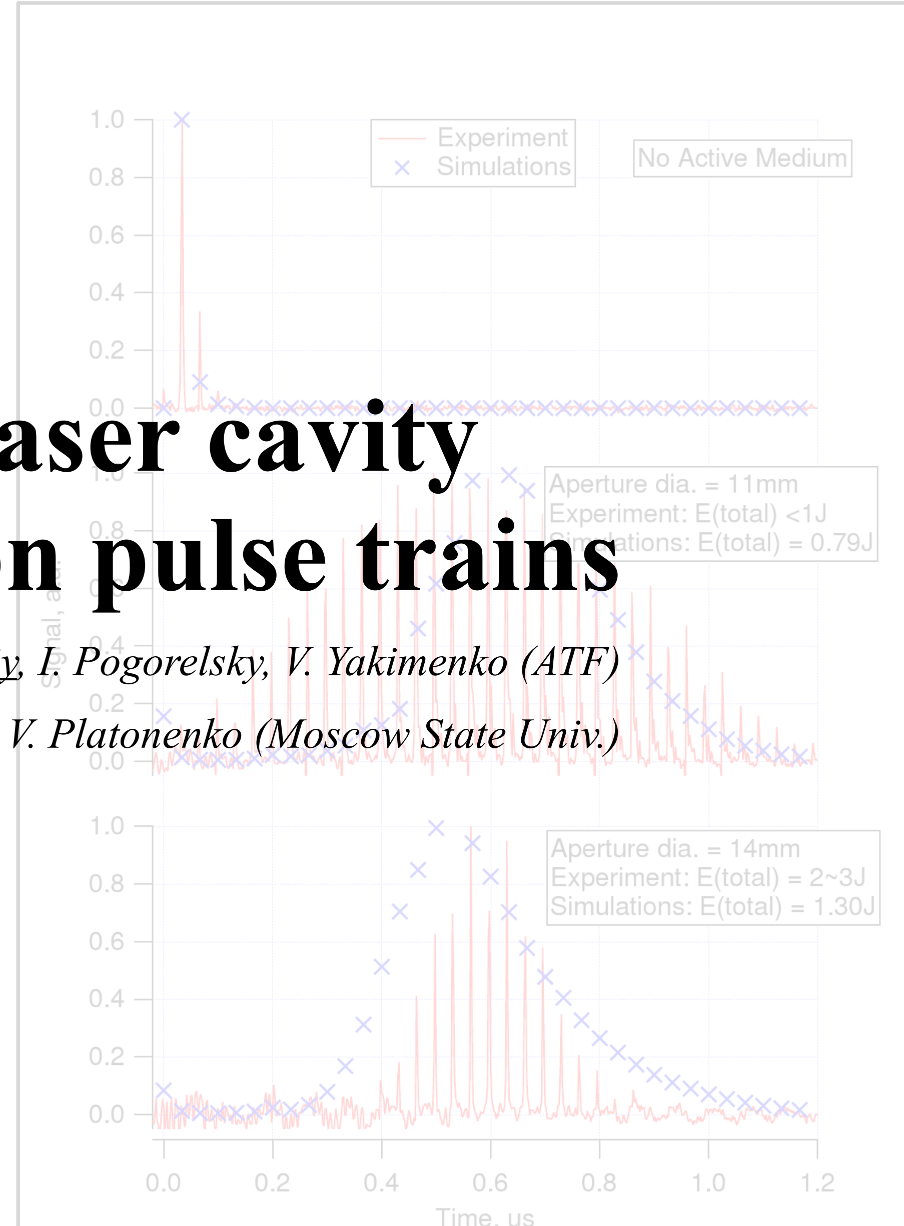




Motivations

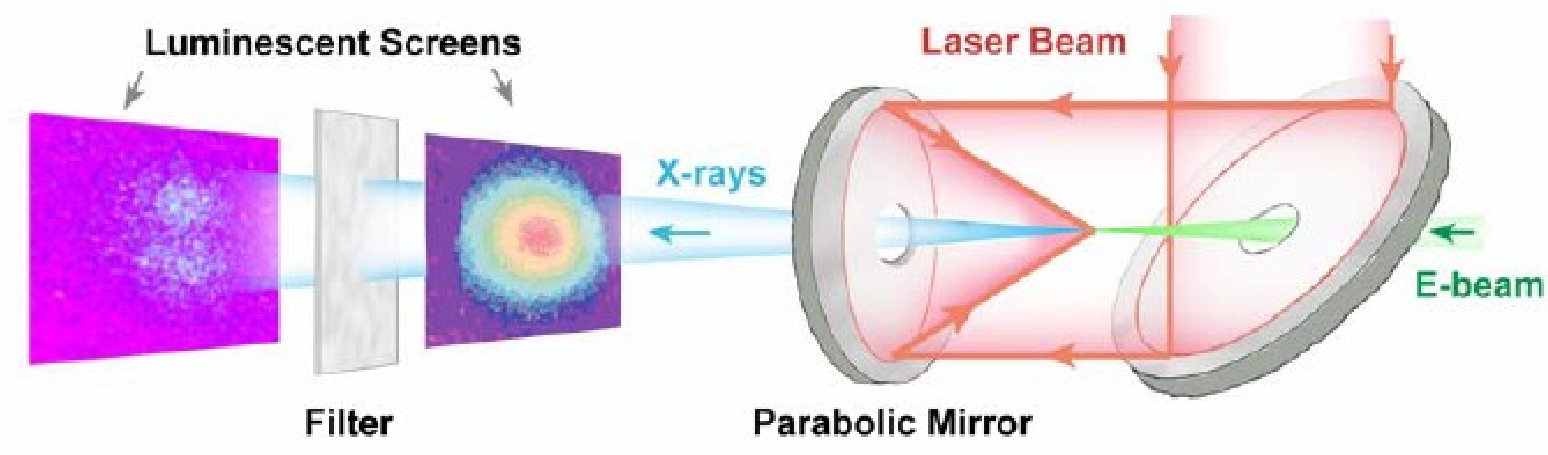
- Polarized positron source for International Linear Collider (ILC)

- Polarized muon beams produced through gamma conversion will compete in brightness and energy efficiency with conventional proton-based sources.

- Multi-kW γ-sources conceivable based on state-of-art CO_2 lasers and energy recovery linacs for rare isotope photofission, transmutation of used nuclear fuel, polarized positron sources for e^+e^- colliders, etc.

- A path to compact pico- and femto-second light sources of the peak and average brightness of the order 10^{25} and 10^{17} (s mm^2 mrad^2 0.1%)$^{-1}$ correspondingly - the orders of magnitude higher than modern light sources.

Prior art: Thomson scattering experiments in ATF

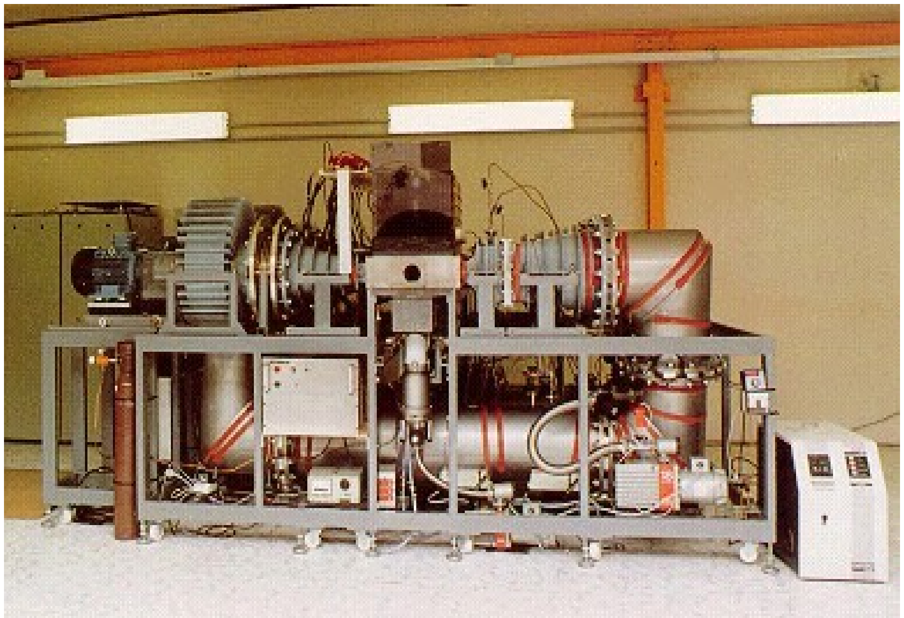


- Started as US/Japan collaboration for ILC positron source
- Record brightness and efficiency were demonstrated
- X-ray source is being used for user experiments to test applicability for material science
- Collaboration with UCLA/Italy brought equipment from ESRF

M. Babzien *et al. Observation of Second Harmonic in Thomson Scattering from Relativistic Electrons.* Phys. Rev. Lett. **96**, 054802 (2006)

Commercially available lasers

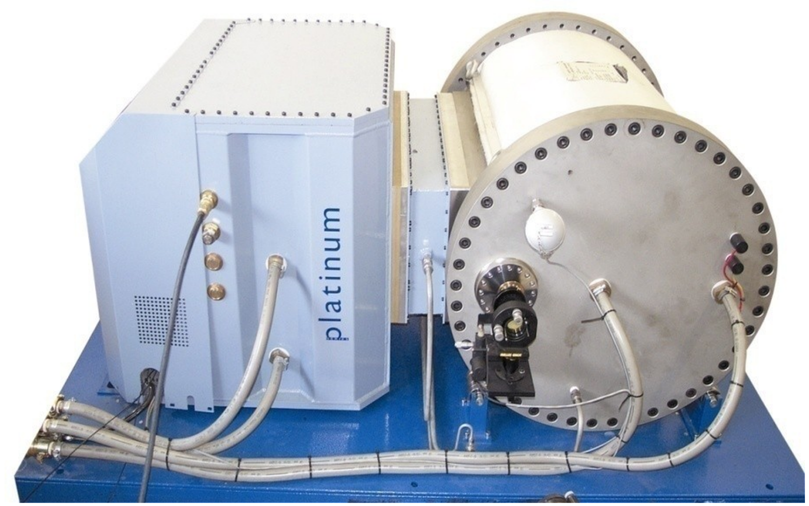
SOPRA (France)



Pressure	5 atm
Beam Size	50 x 50 mm^2
Repetition Rate	100 Hz
Pulse Energy	10 J
Average Power	1 kW
Ionization	x-ray

SDI (South Africa)

Pressure	10 atm
Beam Size	13 x 13 mm^2
Repetition Rate	up to 500 Hz
Pulse Energy	1.5 J
Average Power	750 W
Ionization	UV



Laser specs for ILC

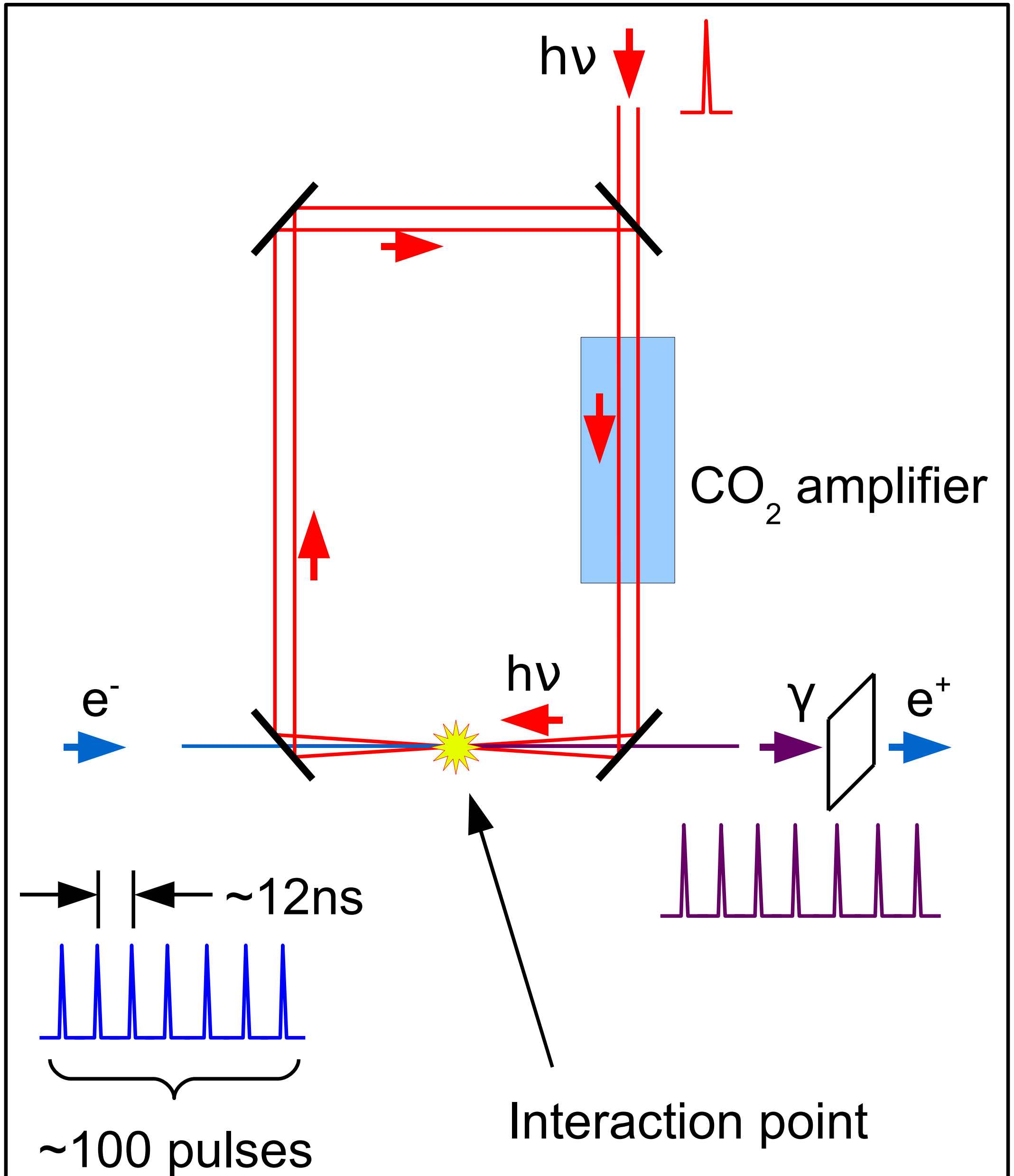
Pulse repetition rate	150 *Hz*
Bunches per pulse	100
Bunch Spacing	12 *ns*
Laser Wavelength	10 μm
Laser energy	1 *J*
Size at focus	40 μm
Laser pulse length	5 *ps*
E-beam energy	6 GeV
e^- bunch	10 nC
Number of γ per electron	1 (per IP)
γ-beam energy	40 MeV
Number of lasers	5
e^+ yield on target	2 %
e^+ bunch	1 nC

- Requires: 15 kHz, 15 kW, picosecond, sub-terawatt CO_2 laser.

- This exceeds capabilities of laser technology by 1-2 orders of magnitude.

- Instead, we propose to reuse laser energy by circulating the pulse inside the laser amplifier cavity that incorporates Compton interaction point (IP).

#*Polarized positron source: the concept*



- *A picosecond CO_2 laser pulse circulates in a ring cavity*

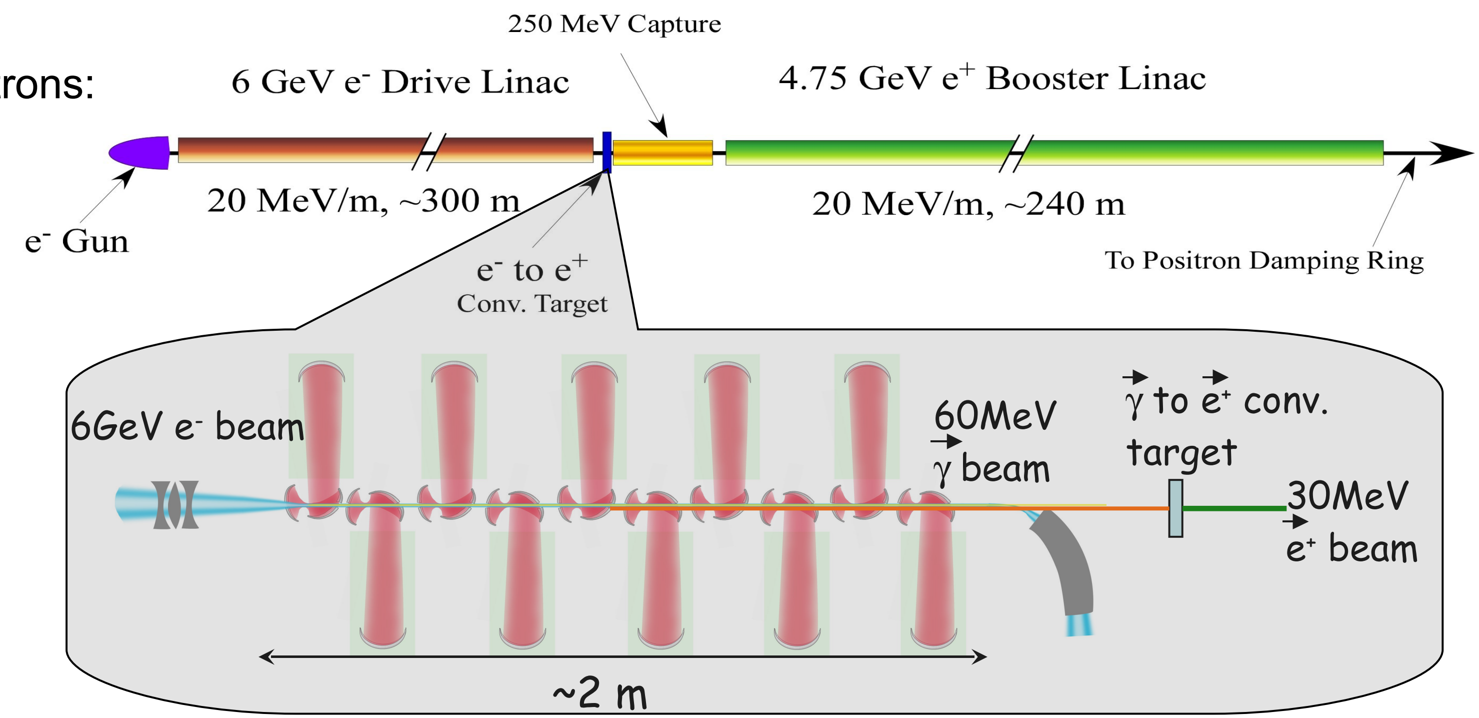
- *At each pass through the cavity the laser pulse interacts with a counter-propagating electron pulse generating γ-quanta* via *Compton scattering*

- *Optical losses are compensated by intracavity amplifier*

- *The λ-proportional number of photons per Joule of laser energy allows for higher γ-yield (compared to solid state lasers)*

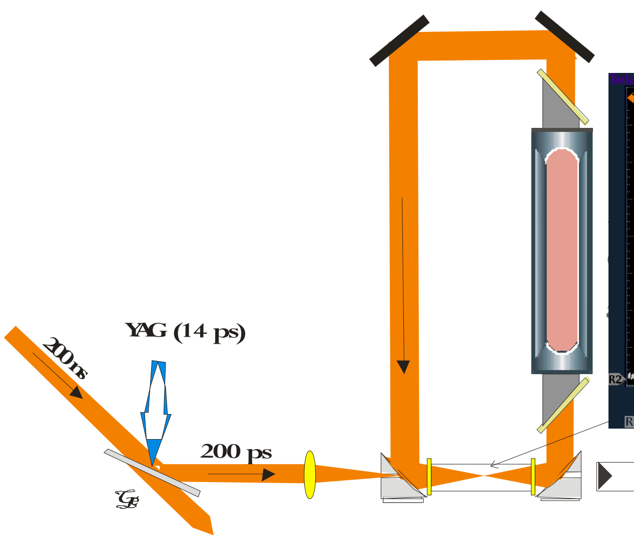
Polarized positron source for ILC, CLIC, Super B

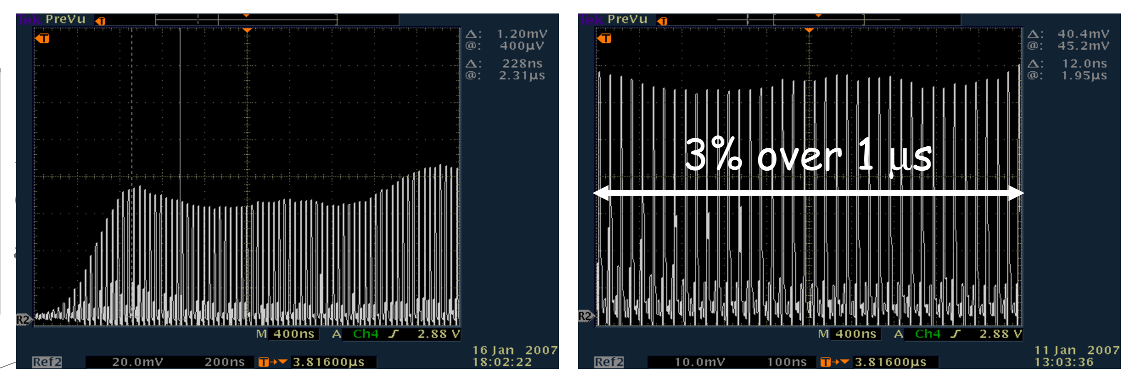
Conventional
Non-Polarized Positrons:



Polarized γ-ray beam is generated in the Compton back scattering inside optical cavity of CO_2 laser beam and 6 GeV e-beam produced by linac.

First tests of the laser cavity





Computer simulations: Model

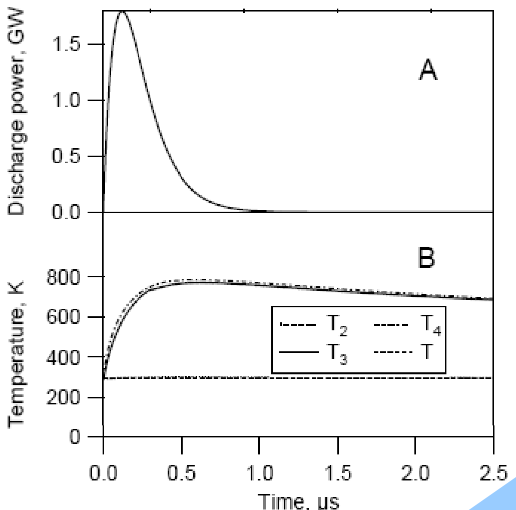
$$2ik\frac{\partial}{\partial z}E = -\nabla_{\perp}E - 4\pi\frac{\omega^2}{c^2}P,$$

$$\frac{\partial}{\partial t}p_J = i(\omega - \omega_J)p_J - \frac{p_J}{\tau_2} - \frac{Ed_J^2}{2i\hbar}\Delta n_J,$$

$$\frac{\partial}{\partial t}\Delta n_J = -\frac{2}{i\hbar}(Ep_J - c.c.) - \frac{\Delta n_J - \Delta n_J^0}{\tau_r}$$

Beam Propagation
(diffraction, optics, losses)

Amplification & Rotational relaxation
(fast time-scale)

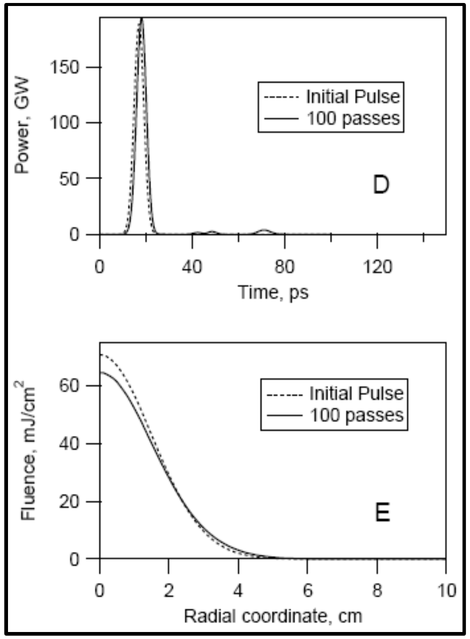


Vibrational relaxation
(slow time-scale)

Pumping
(slow time-scale)

Boltzmann equations
(discharge energy distribution)

Discharge dynamics



Spectra
(amplification band)

Using data from HITRAN2004
and CDSD spectroscopic databases

Computer simulations: Software

- *Based on numerical solution of* *Maxwell-Bloch* *equations*

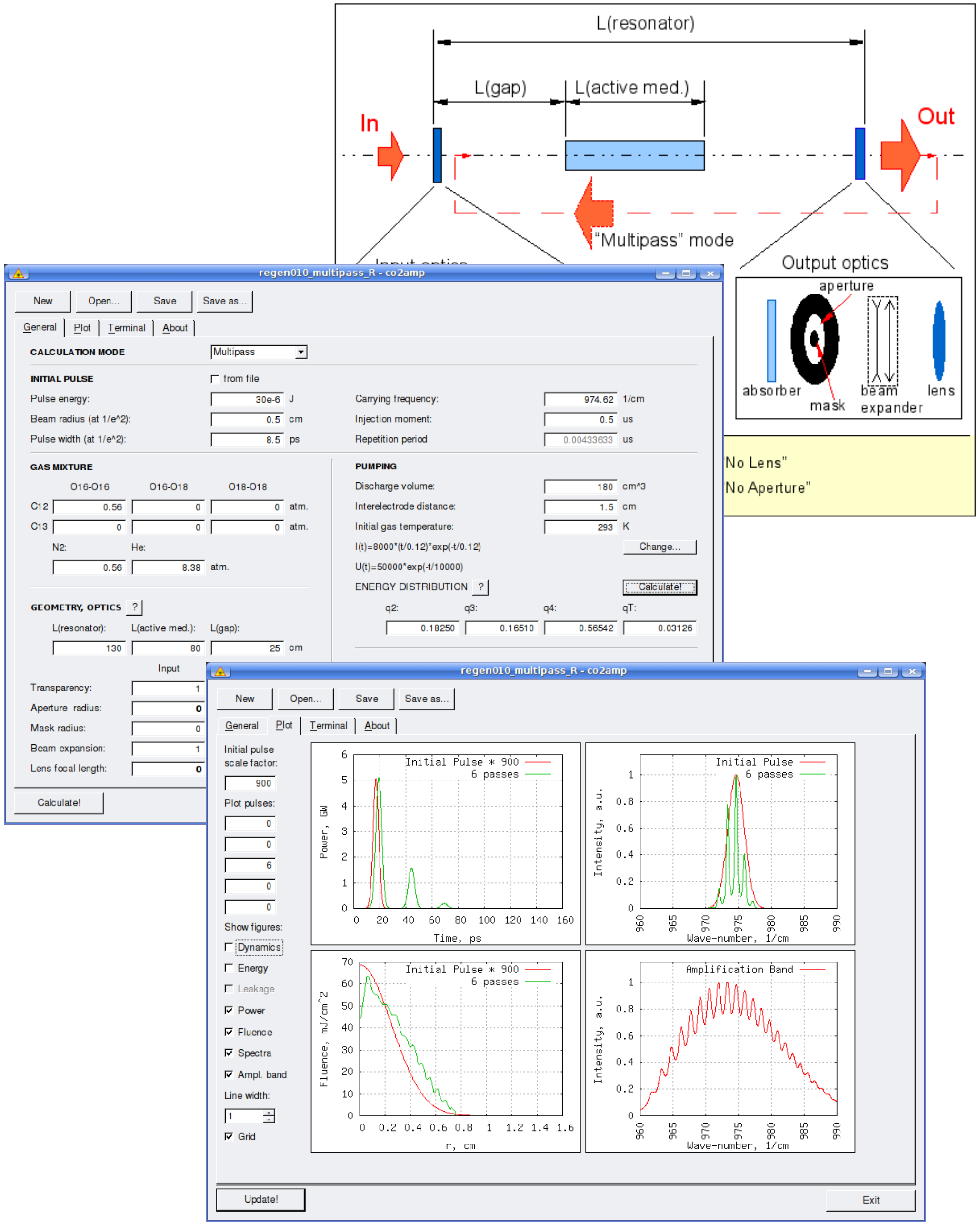
- *Accurate* *molecular dynamics* *simulation*

- *Realistic pumping* *model*

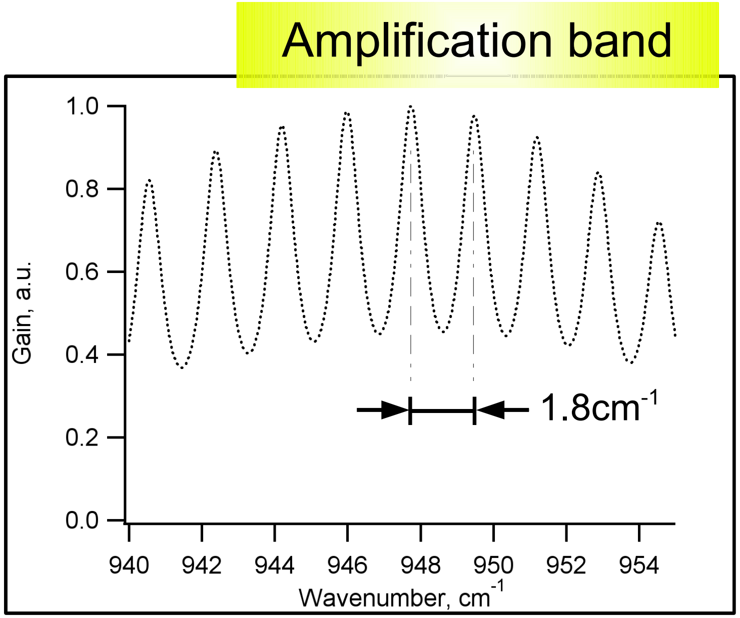
- *Beam propagation* *algorithm based on diffraction theory*

- *Possibility to simulate* CO_2 *isotopic mixtures*

- *Modern* *GUI* *shell for fast learning and easy operation*



Pulse splitting problem



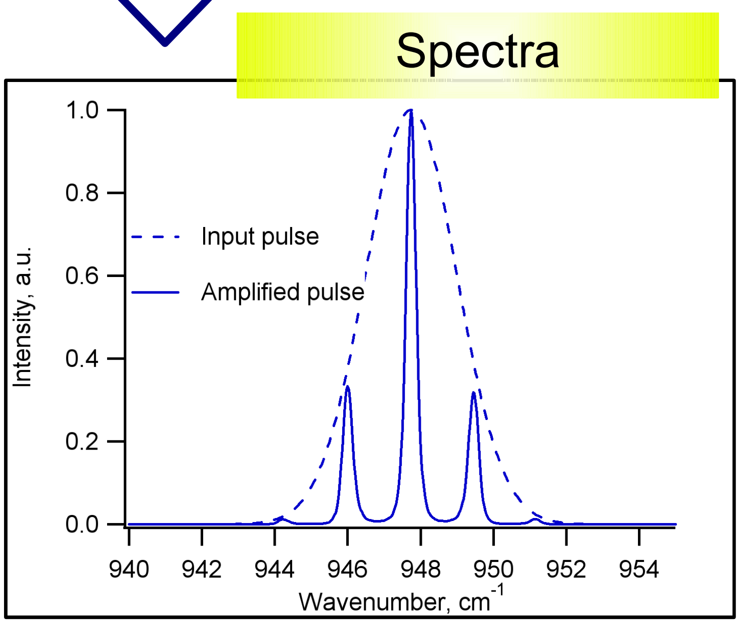
__Case shown:__

Pulse length: 5 ps (fwhm)

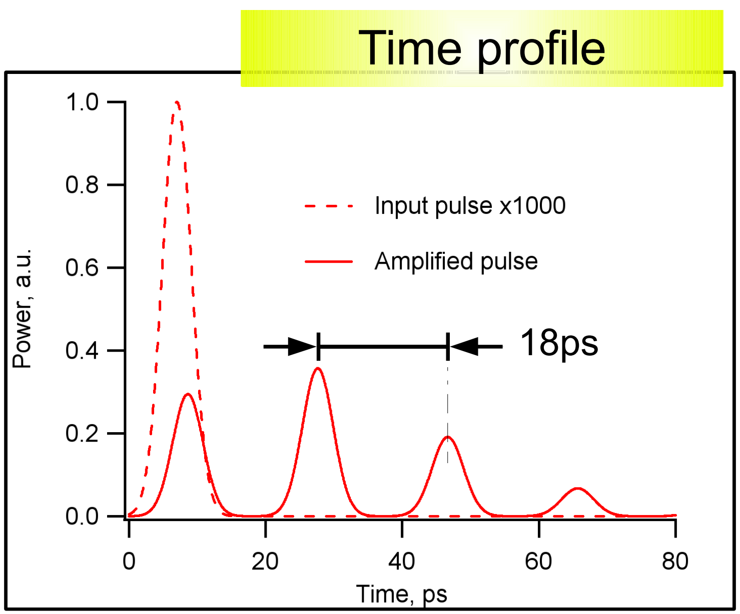
Gas pressure: 7.5 atm

Branch: 10P (10.6 μm)

Amplification: 1000x



Fourier transform.



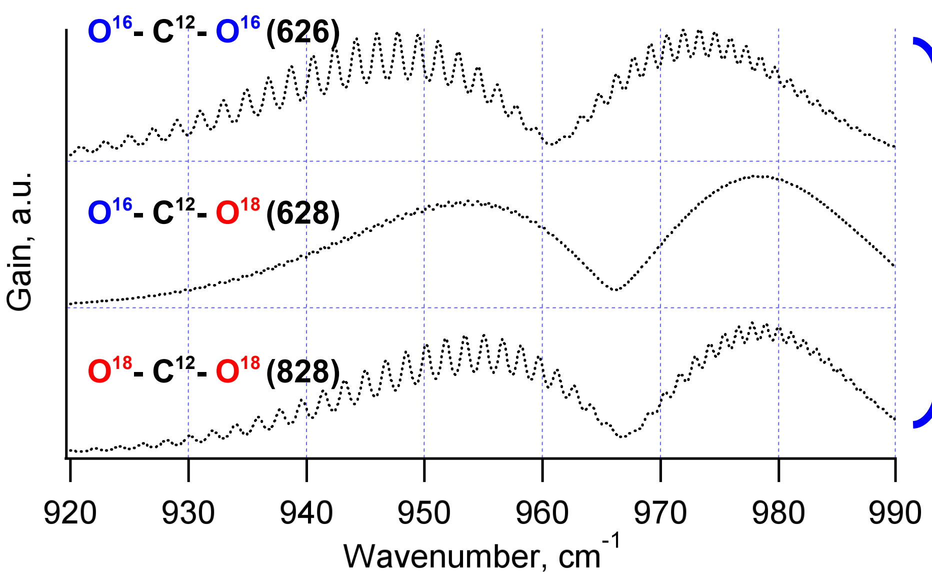
Addressing pulse splitting: “Smoothing” of gain spectrum

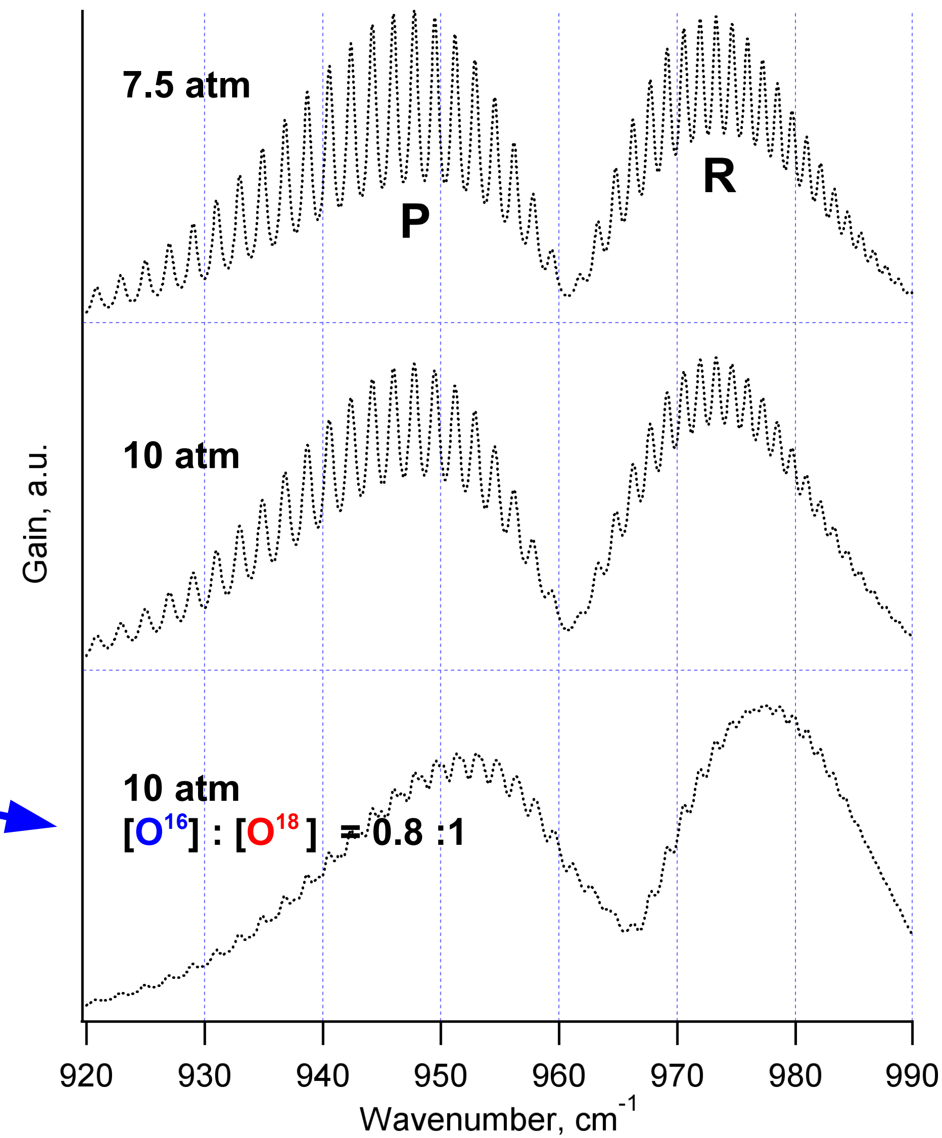
1) R-branch *vs.* P-branch: smaller line spacing (1.3 cm^{-1} and 1.8 cm^{-1} respectively)

2) Increased pressure: pressure broadening

3) Isotopic mixture: higher effective line density

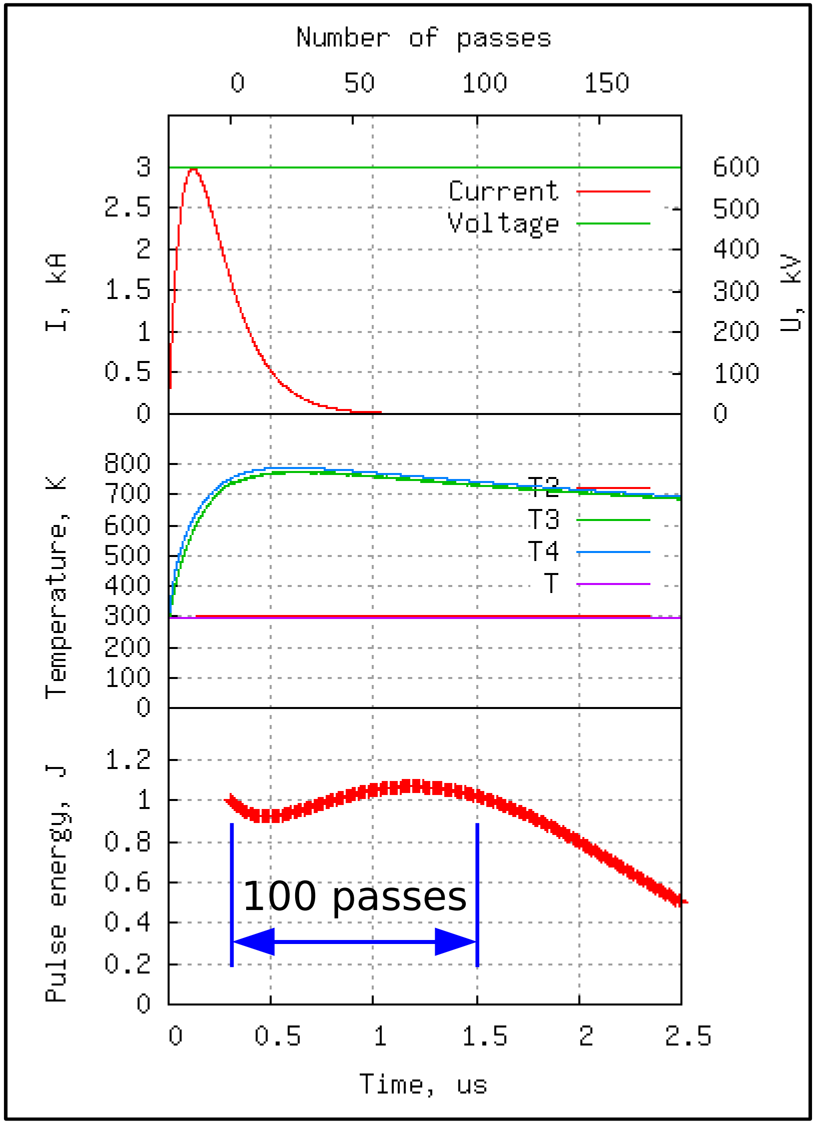
=> Smoother gain spectrum

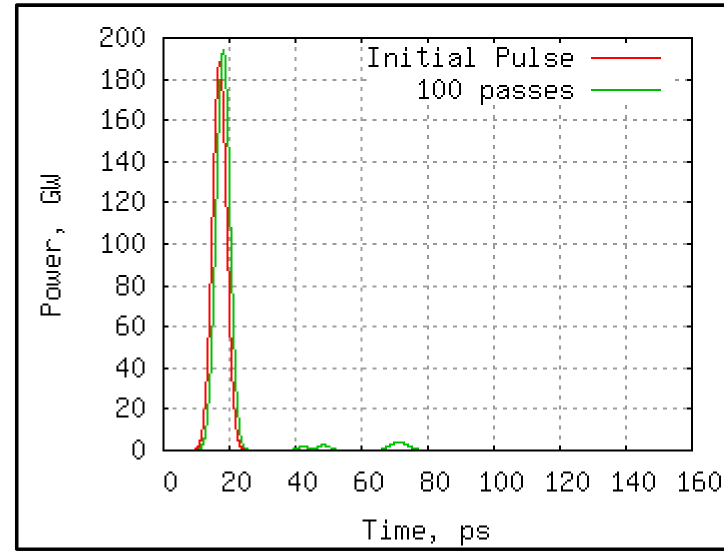


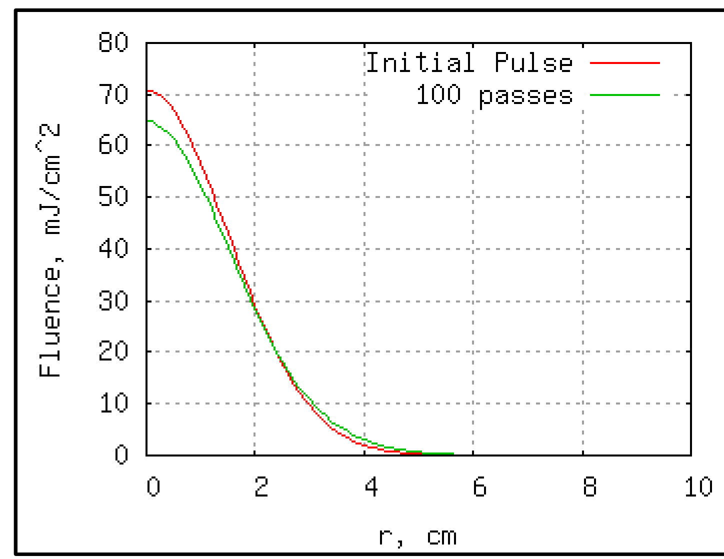


Computer simulations: multipass dynamics

- Pressure:
  5 atm
- Pulse energy:
  1 J
- Pulse length:
  5 ps (fwhm)
- Roundtrip time:
  12 ns
- Wavelength:
  10.2 μm (R-br.)
- Optical losses:
  5% / pass
- Gas mixture:
  0.5 : 3 : 6.5
- Isotopes:
  $[O^{16}] : [O^{18}] = 0.8 : 1$

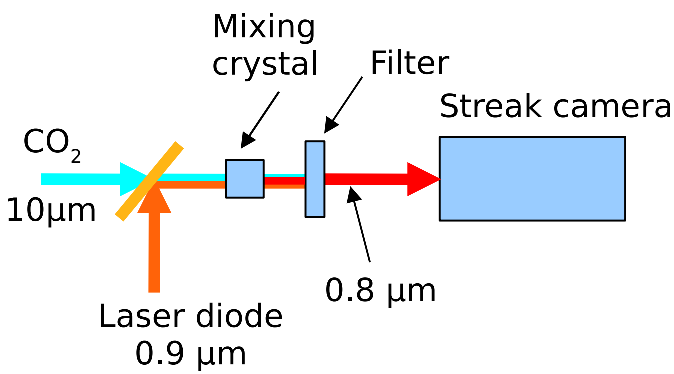


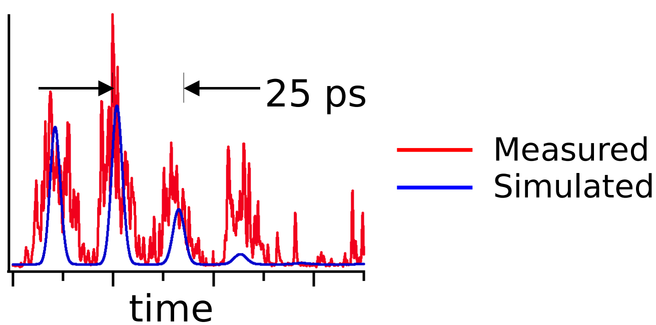




Pulse diagnostics

"Streak camera"



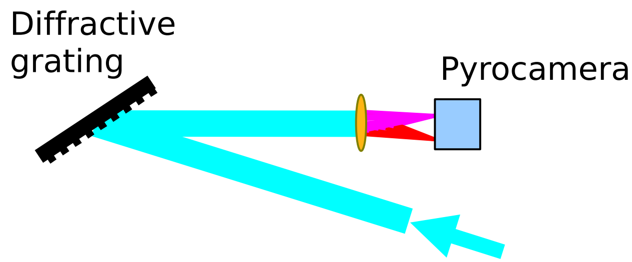


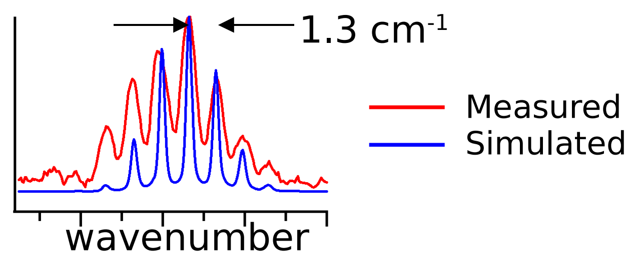
:) Single-shot

:(Low resolution (~10 ps)

:) Train measurements

"Spectrometer"





Fourier transform

Total bandwidth <=> Individual pulse
sub-ps resolution

Individual lines <=> Train
resolution improvement needed

:) Single-shot

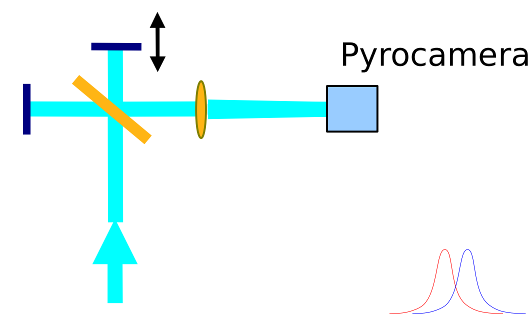
:) Simple = reliable

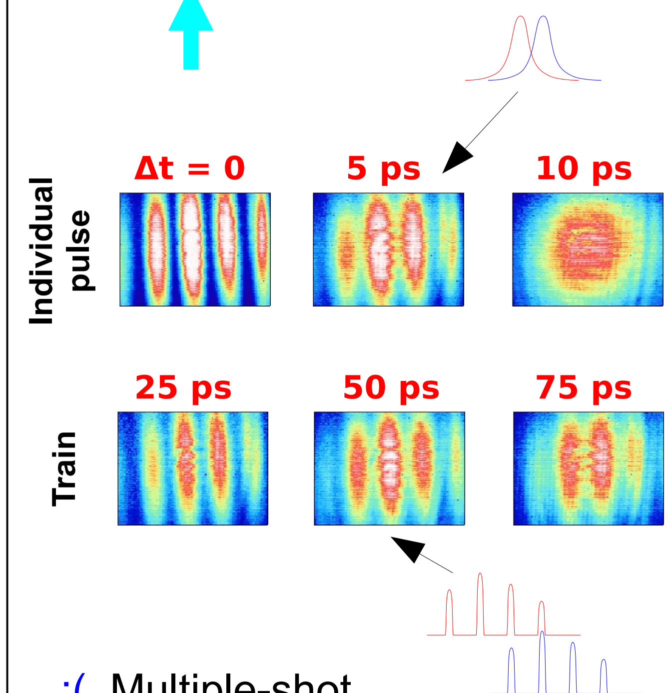
:) Indiv. pulse measurements

... Train measurements (?)

:(Indirect method

"Interferometer"





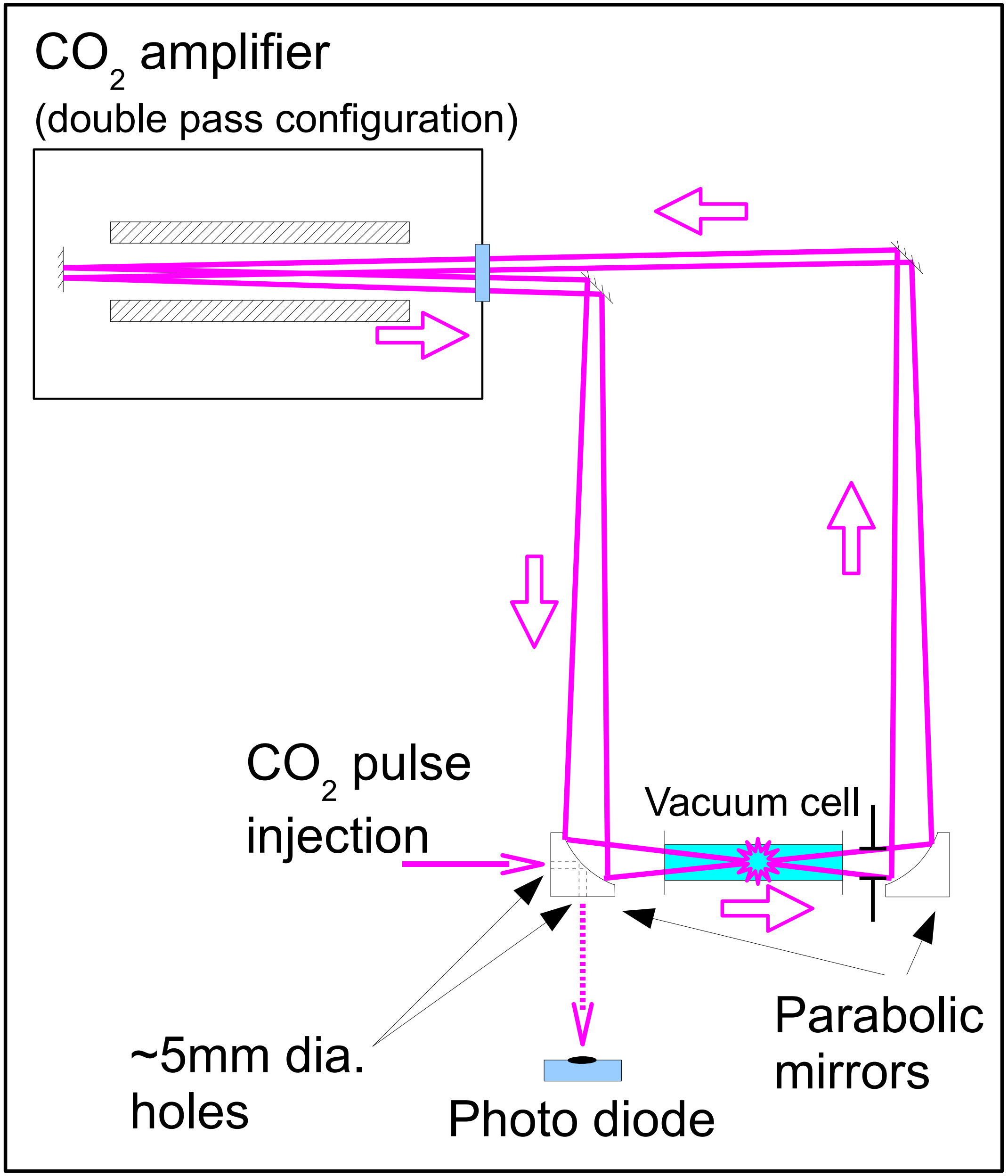
:(Multiple-shot

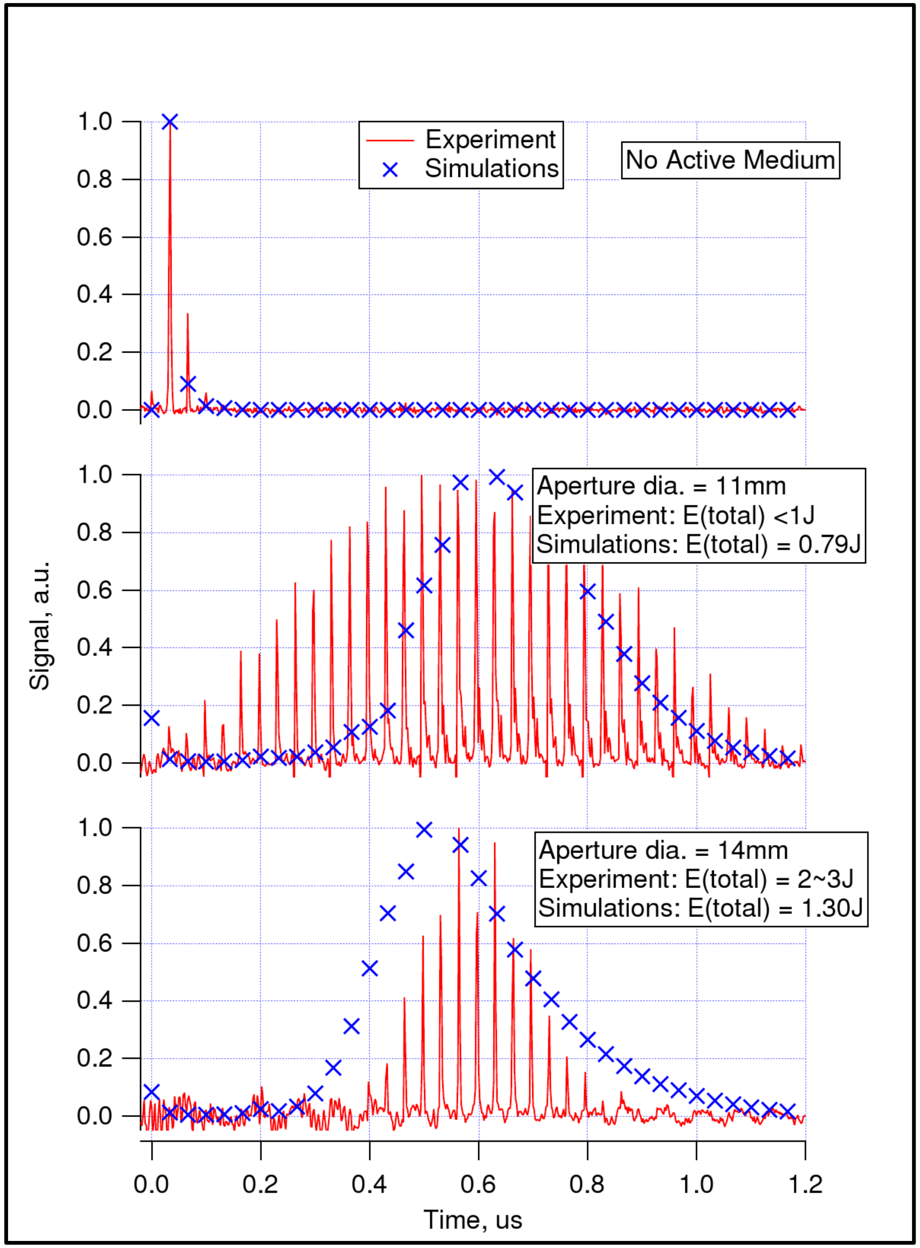
:) Indiv. pulse measurements

:) Train measurements

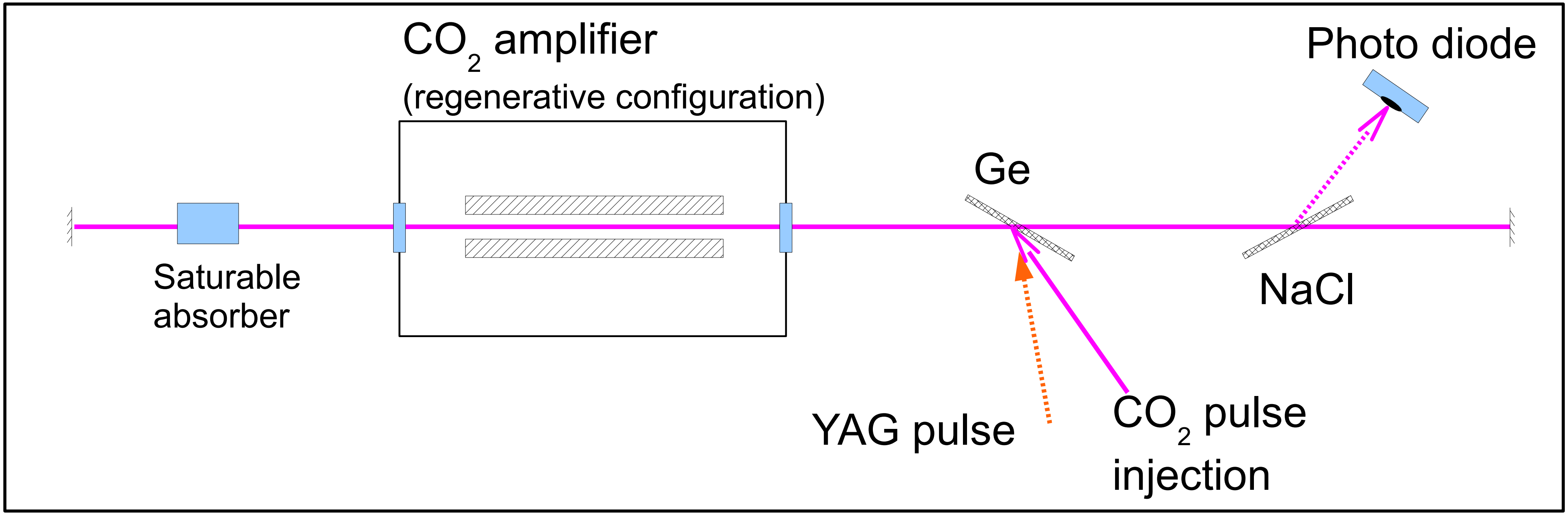
:(Complicated data analysis

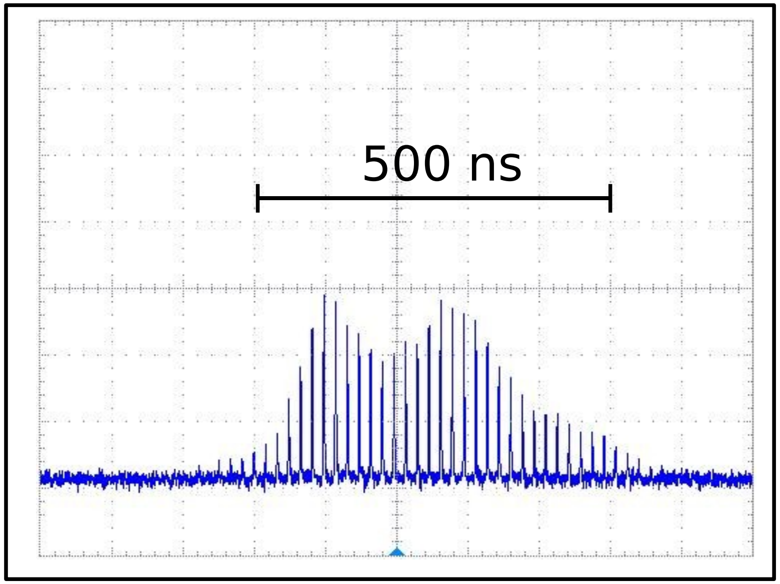
Test I: Pulse injection through a holed mirror





Test II: Pulse injection using a semiconductor switch





Demonstrated:

- Multipass picosecond CO_2 laser pulse amplification and energy sustain

- Pulse injection *via* semiconductor switch

- Qualitative agreement between experiment and computer simulations

Summary and conclusions

- Advanced computer program for simulation of short pulse amplification in multipass cavity is developed
- Diagnostics tools for measuring (sub-) picosecond pulse duration and time profile are implemented
- Preferred regimes of picosecond pulse amplification in multipass cavity are determined using a newly developed simulation software
- Advantage of isotopic CO_2 mixture is demonstrated in computer simulations
- Qualitative agreement between proof-of-principle experiment results and computer simulations is achieved