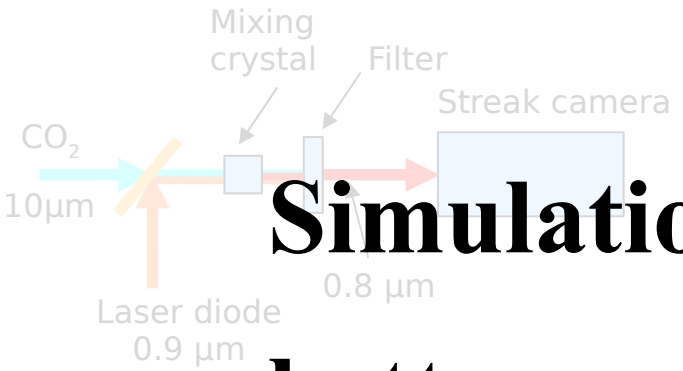
Simulation and diagnostic tools for better understanding and upgrade of the CO_2 laser

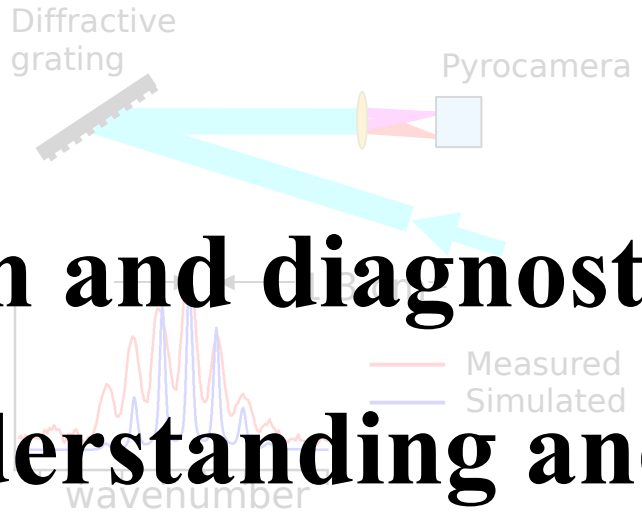
Mikhail Polyanskiy, ATF



:) Single-shot

:(Low resolution (~10 ps)

:) Train measurements



:) Single-shot

:) Simple = reliable

:) Indiv. pulse measurements

... Train measurements (?)

:(Indirect method

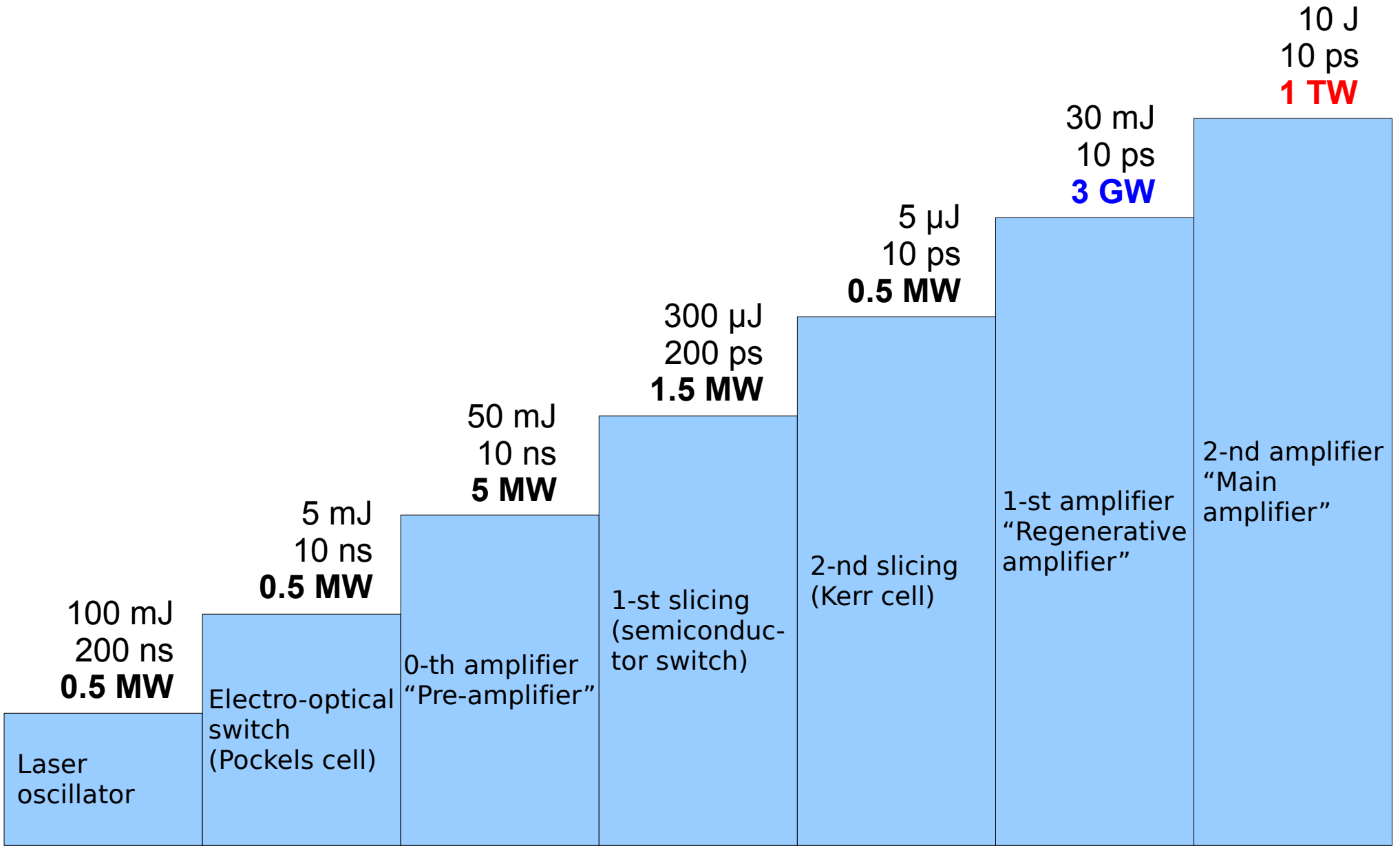
:(Multiple-shot

:) Indiv. pulse measurements

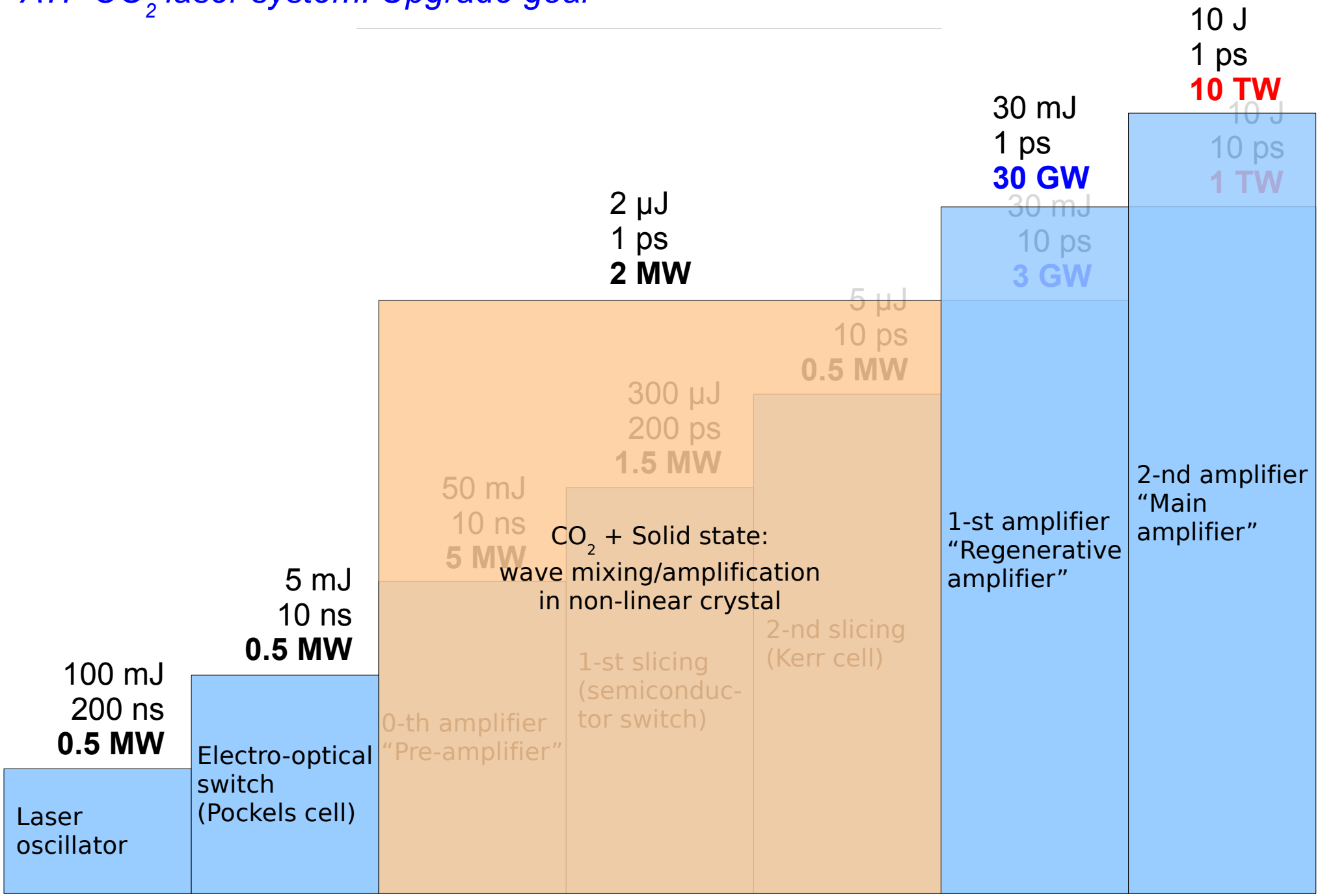
:) Train measurements

:(Complicated data analysis

ATF CO_2 laser system



ATF CO_2 laser system: Upgrade goal



Motivations for computer simulations

- Multipass Compton cavity project
  (presentation on April 2)

- Pulse splitting problem
  (this presentation)

- Move towards sub-picosecond pulse
  (this presentation)

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)

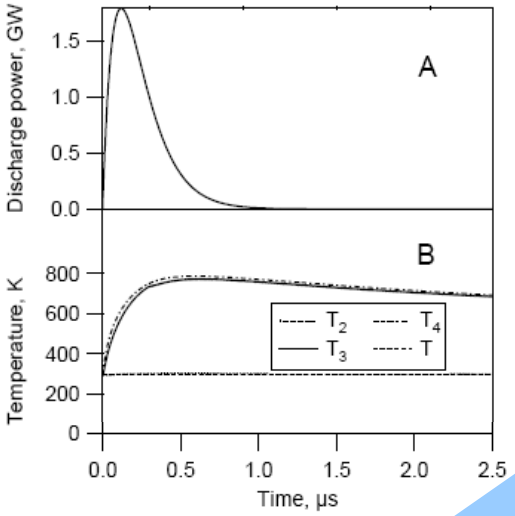
Amplification & Rotational relaxation
(fast time-scale)

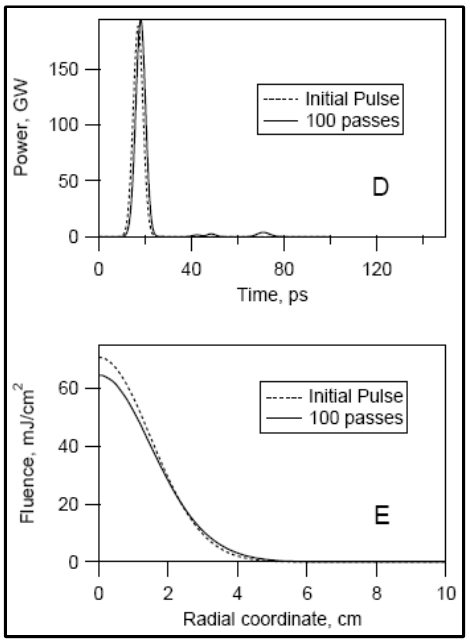
Vibrational relaxation
(slow time-scale)

Pumping
(slow time-scale)

Boltzmann equations
(discharge energy distribution)

Discharge dynamics





Spectra
(amplification band)

Using data from HITRAN-2004 spectroscopic database

Computer simulations: Software

- Based on numerical solution of Maxwell-Bloch equations

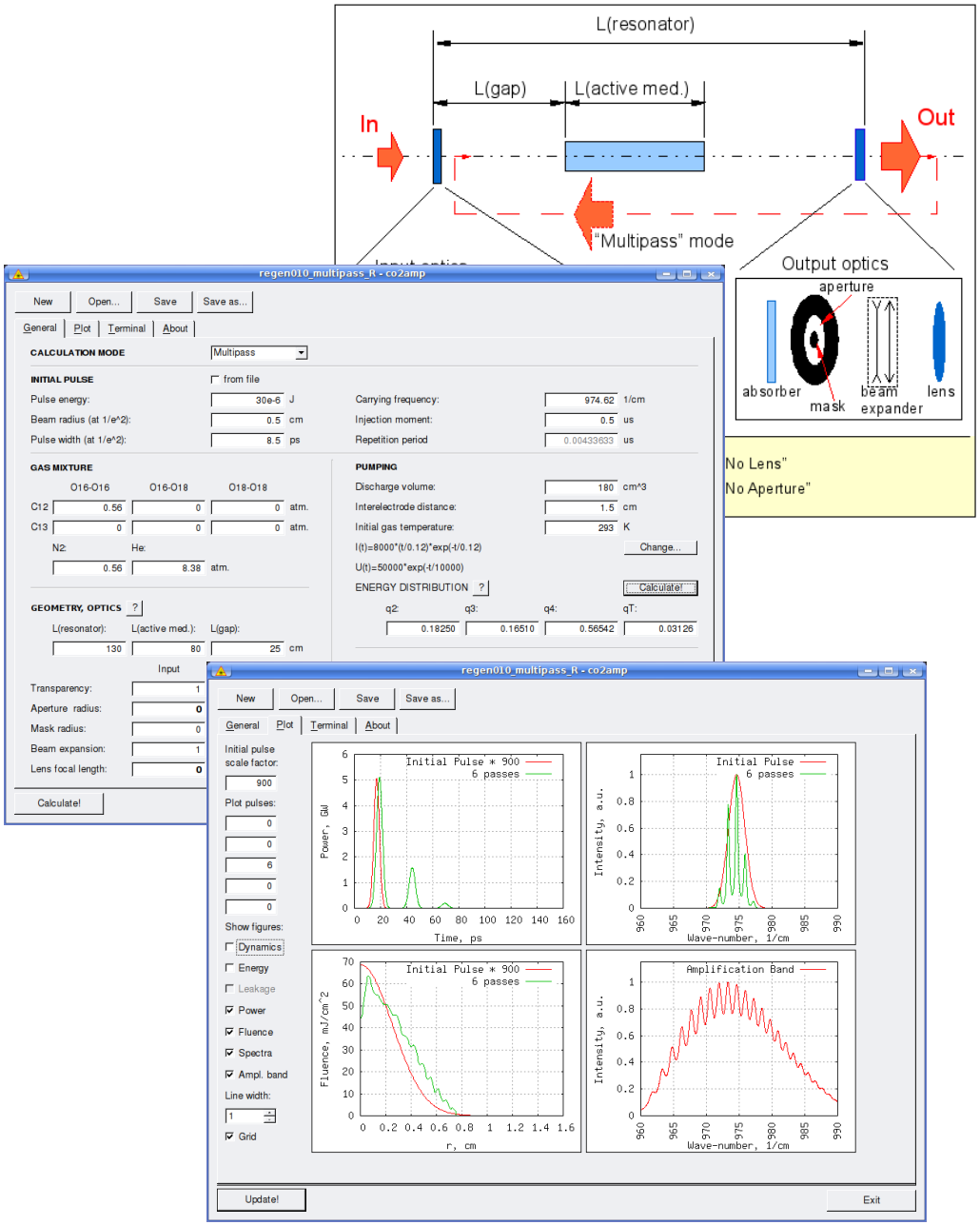
- Accurate molecular dynamics simulation

- Realistic pumping model

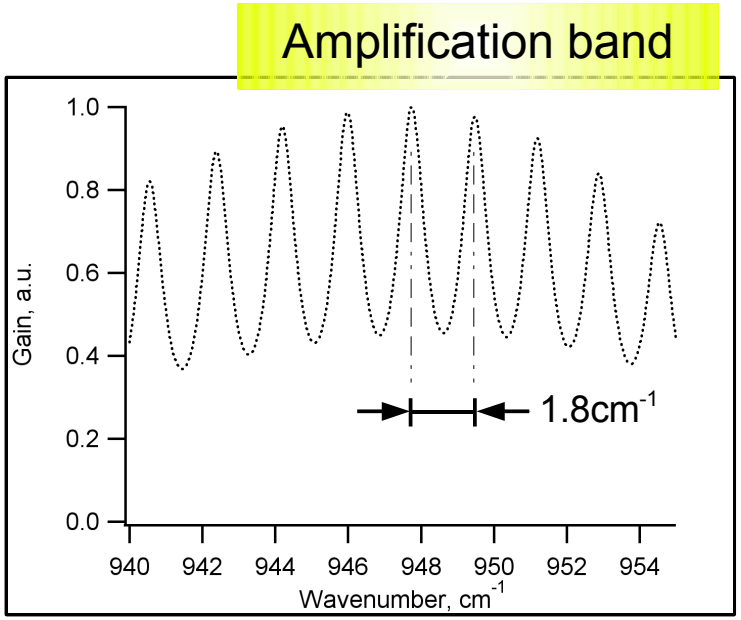
- Beam propagation algorithm based on diffraction theory

- Possibility to simulate CO_2 isotopic mixtures

- Modern GUI shell for fast learning and easy operation

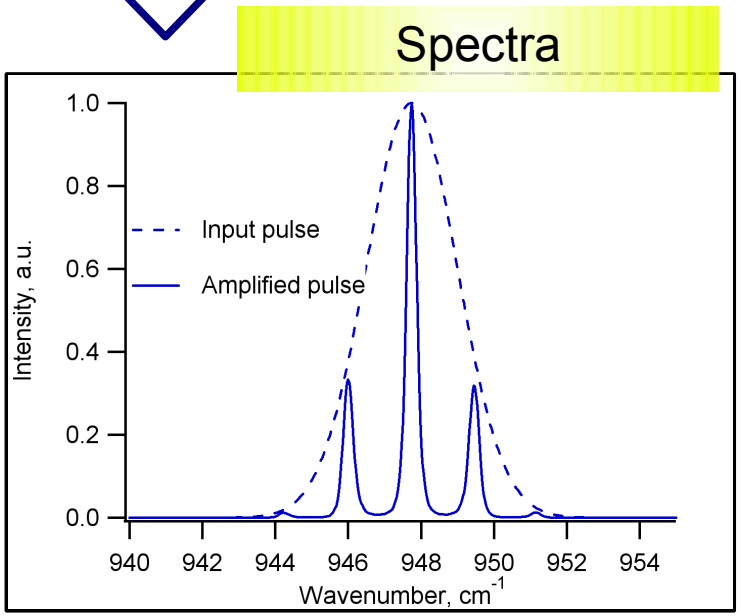


Pulse splitting problem

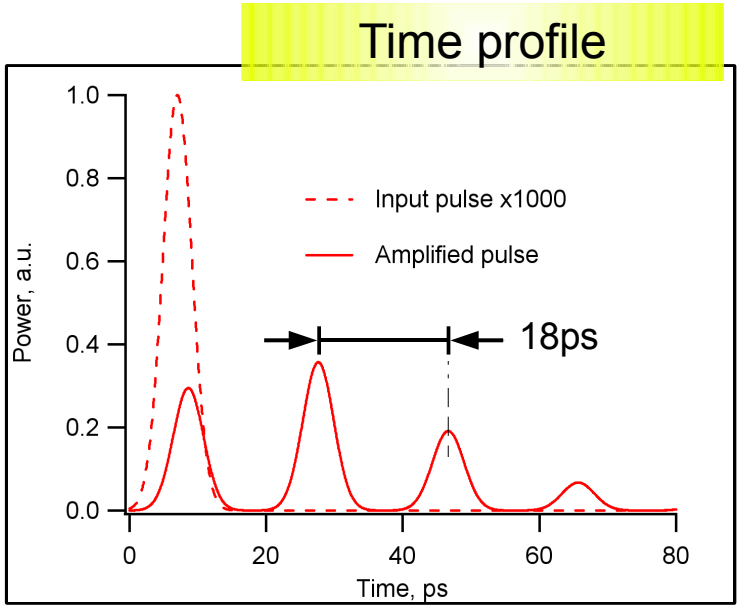


Case shown:

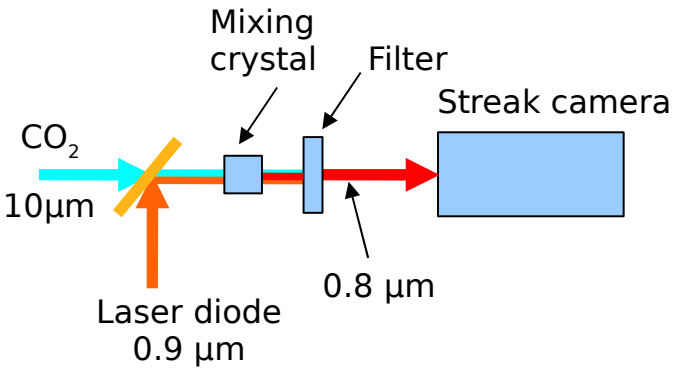
Pulse length:	5 ps (fwhm)
Gas pressure:	7.5 atm
Branch:	10P (10.6 μm)
Amplification:	1000x

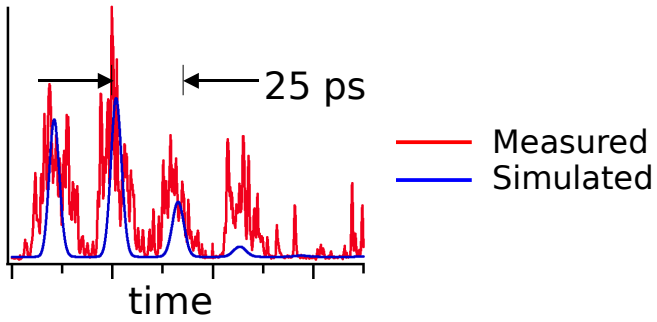


Fourier transform.



"Streak camera"



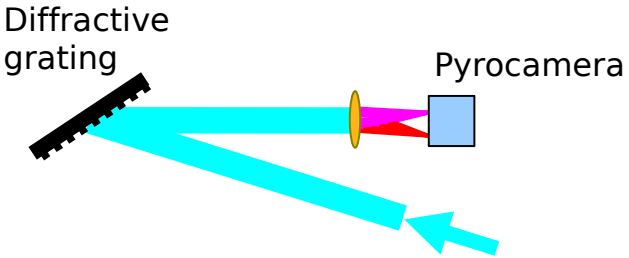


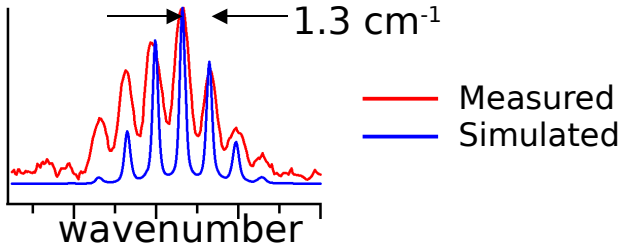
:) Single-shot

:(Low resolution (~10 ps)

:) Train measurements

"Spectrometer"





Fourier transform

Total bandwidth <=> Individual pulse

sub-ps resolution

Individual lines <=> Train

resolution improvement needed

:) Single-shot

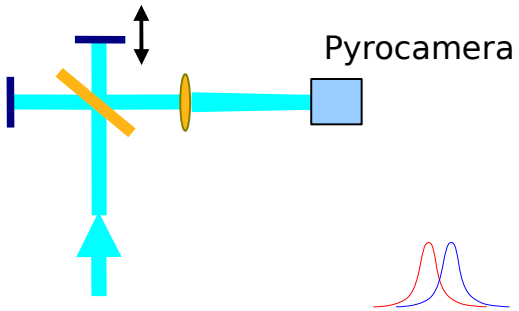
:) Simple = reliable

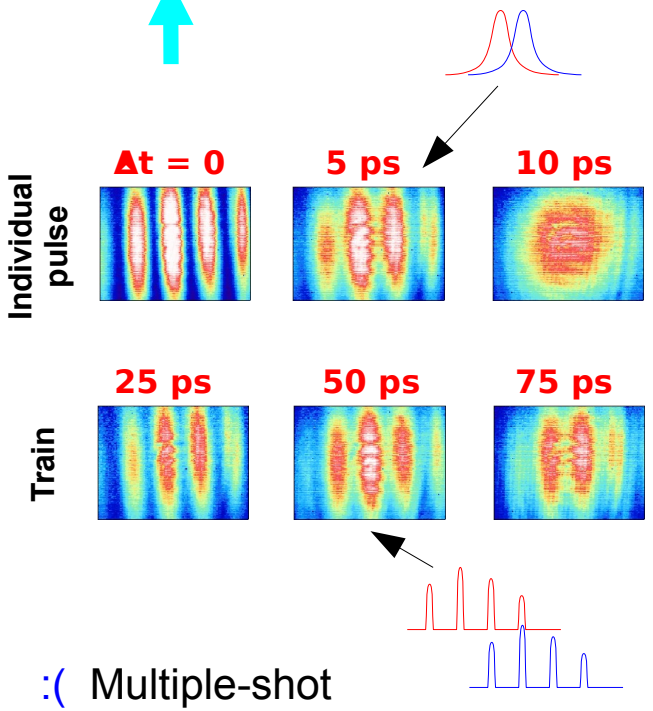
:) Indiv. pulse measurements

... Train measurements (?)

:(Indirect method

"Interferometer"





:(Multiple-shot

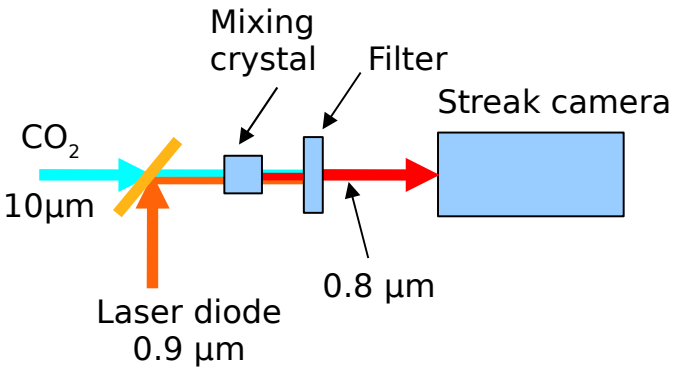
:) Indiv. pulse measurements

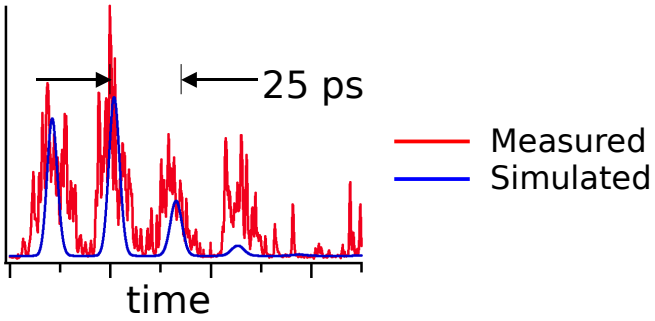
:) Train measurements

:(Complicated data analysis

Diagnostics I: Streak camera (measuring pulse splitting)

"Streak camera"





:) Single-shot

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:) Train measurements

"Spectrometer"

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"Interferometer"

:(Multiple-shot

:) Indiv. pulse measurements

:) Train measurements

:(Complicated data analysis

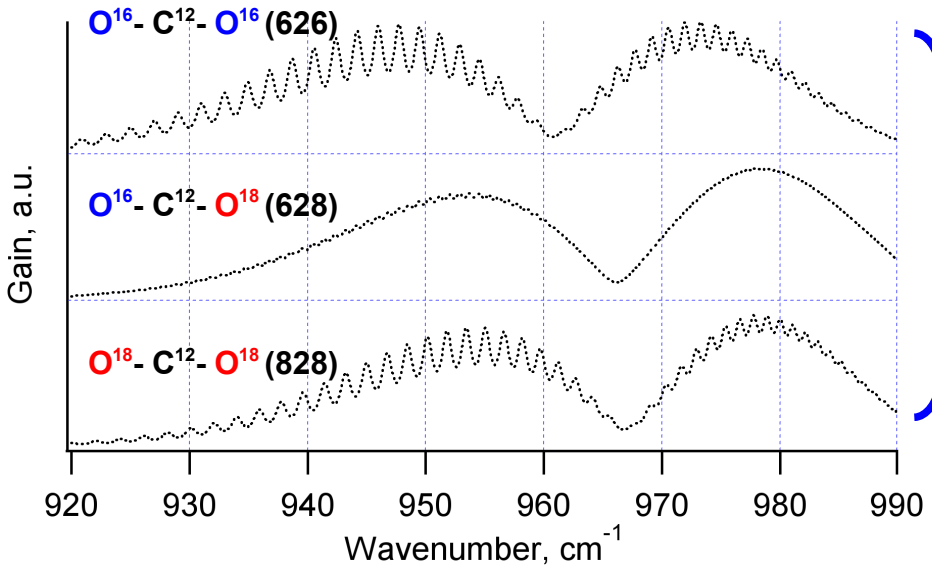
Addressing pulse splitting: "Smoothing" of gain spectrum

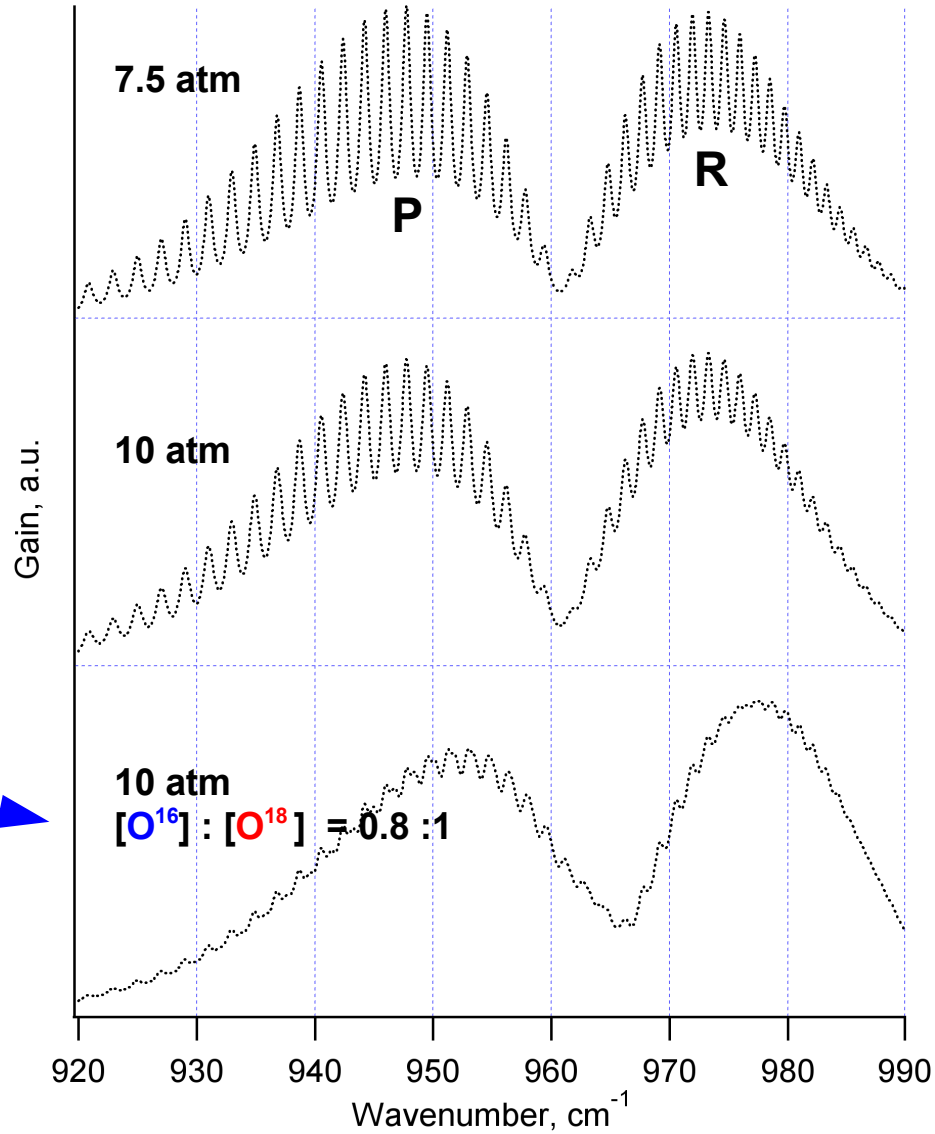
1) R-branch *vs.* P-branch: smaller line spacing (1.3 cm^{-1} and 1.8 cm^{-1} respectively)

2) Increased pressure: pressure broadening

3) Isotopic mixture: higher effective line density

=> Smoother gain spectrum





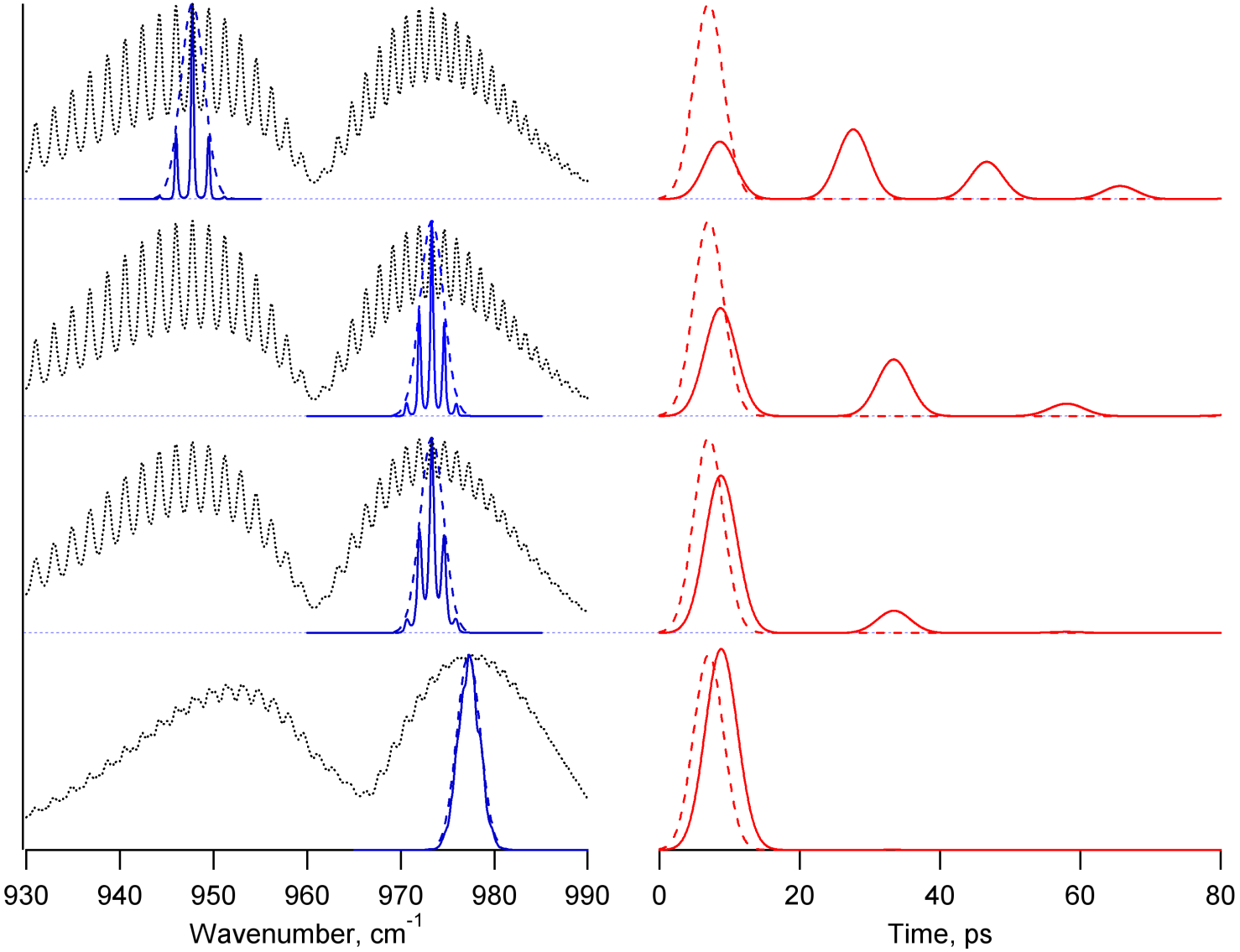
Addressing pulse splitting: "Smoothing" of gain spectrum

7.5 atm; P-branch

7.5 atm; R-branch

10 atm; R-branch

10 atm; R-branch; isotopic gas



Gain profile

Input pulse: Power x 1 000 Spectra

Amplified pulse: Power Spectra

Amplification: 1 000x

Addressing pulse splitting: Minimizing losses

For fixed *net* amplification:

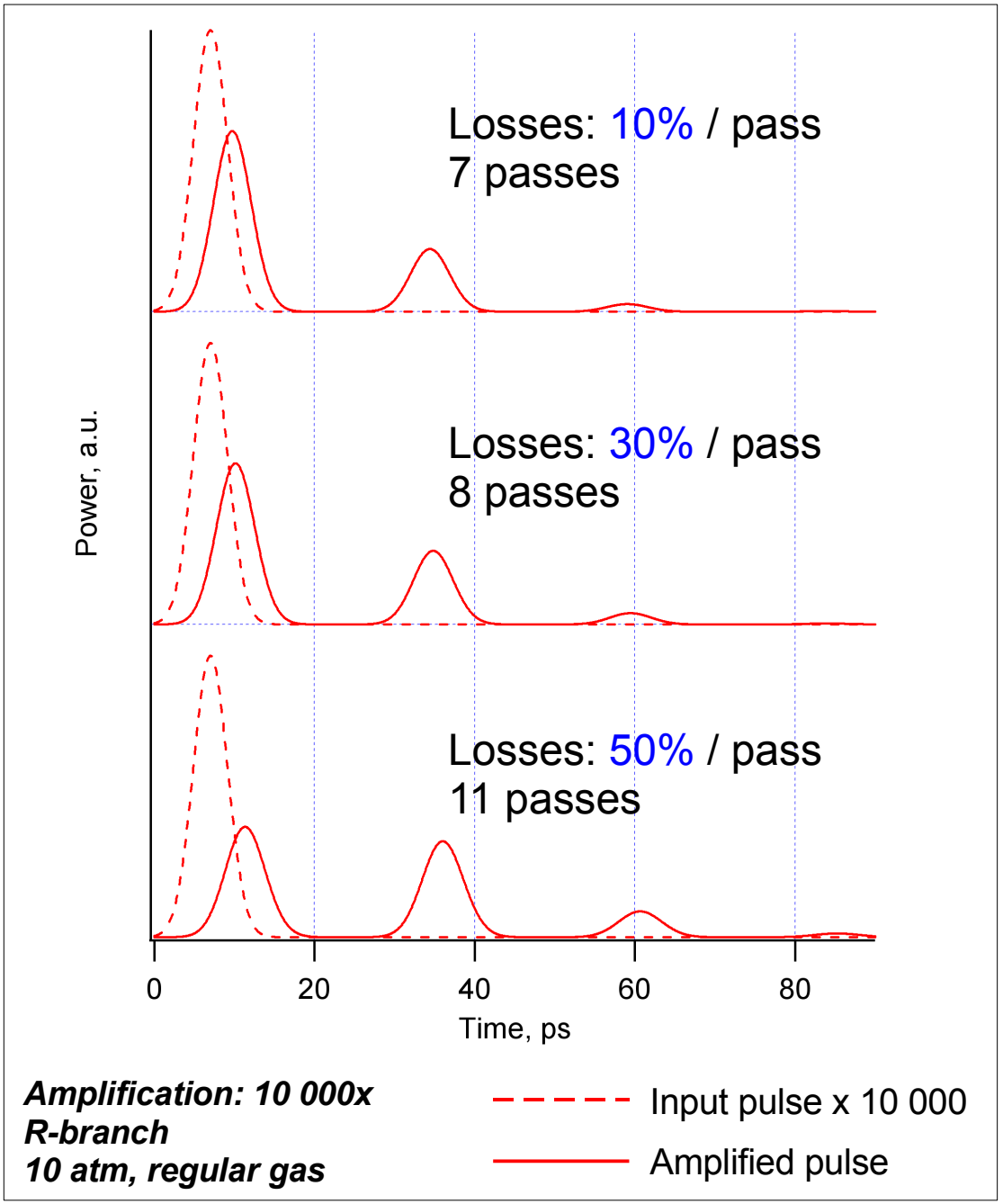
Losses ↑ =>

Gross amplification (number of passes) ↑ =>

Splitting ↑

Sources of losses:

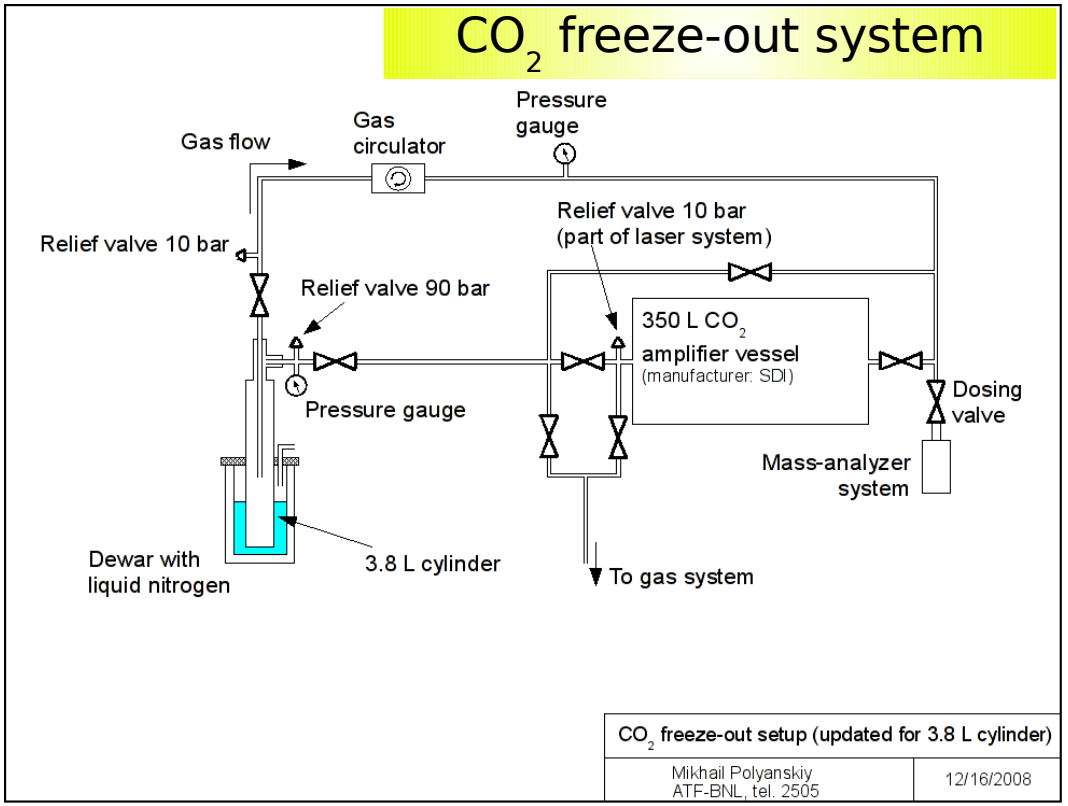
- diffraction
- optics transmittance/reflectance
- optics damages
- misalignments
- ...



Addressing pulse splitting: Summary and status

Recommendations:

- Maximize pressure: *safety approval is in progress for 7.5 atm to 10 atm move* (“main” amplifier)
- Switch to R-branch: *done*
- Use isotopes: *safety approval is in progress for gas system upgrade (“regenerative” amplifier)*
- Minimize losses: *continuous effort for optical system optimization*



Diagnostics II: Spectrometer (measuring individual pulse duration)

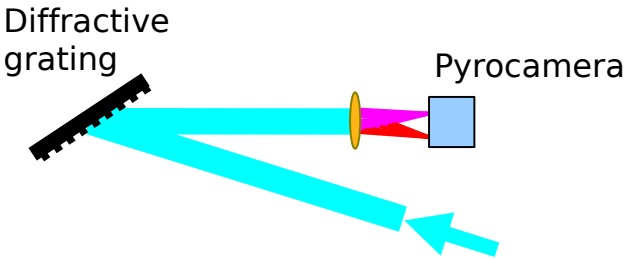
"Streak camera"

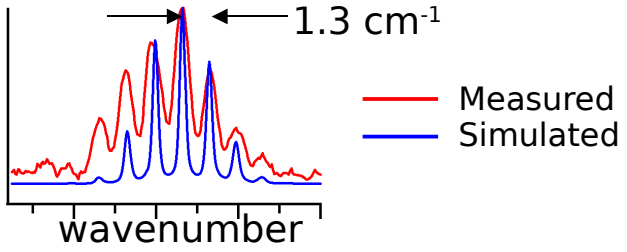
:) Single-shot

:(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

Diagnostics III: Interferometer (independent test)

"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

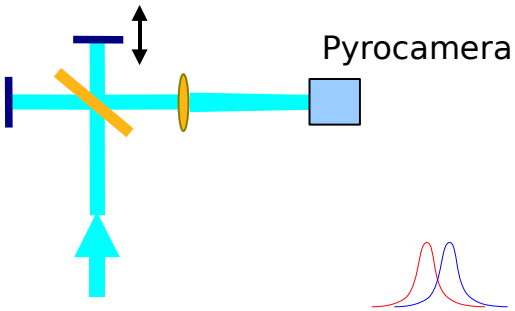
:) Simple = reliable

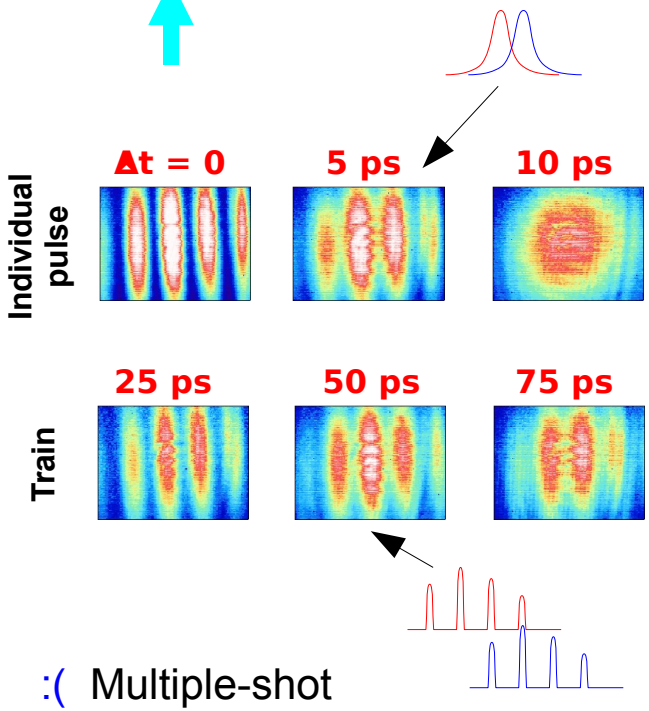
:) Indiv. pulse measurements

... Train measurements (?)

:(Indirect method

"Interferometer"





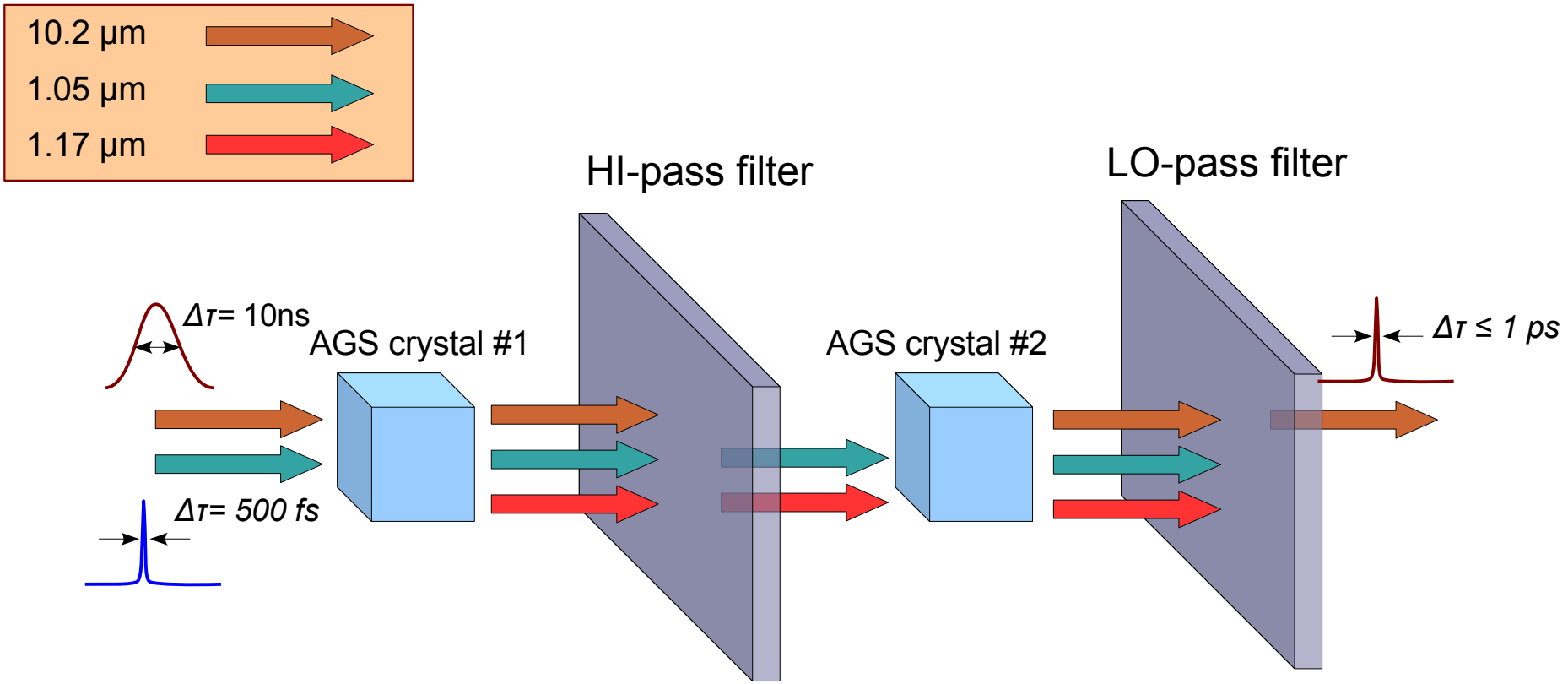
:(Multiple-shot

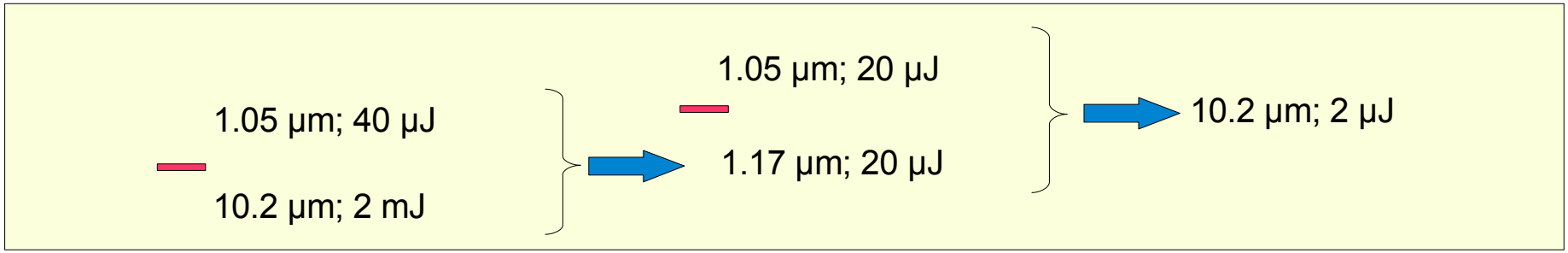
:) Indiv. pulse measurements

:) Train measurements

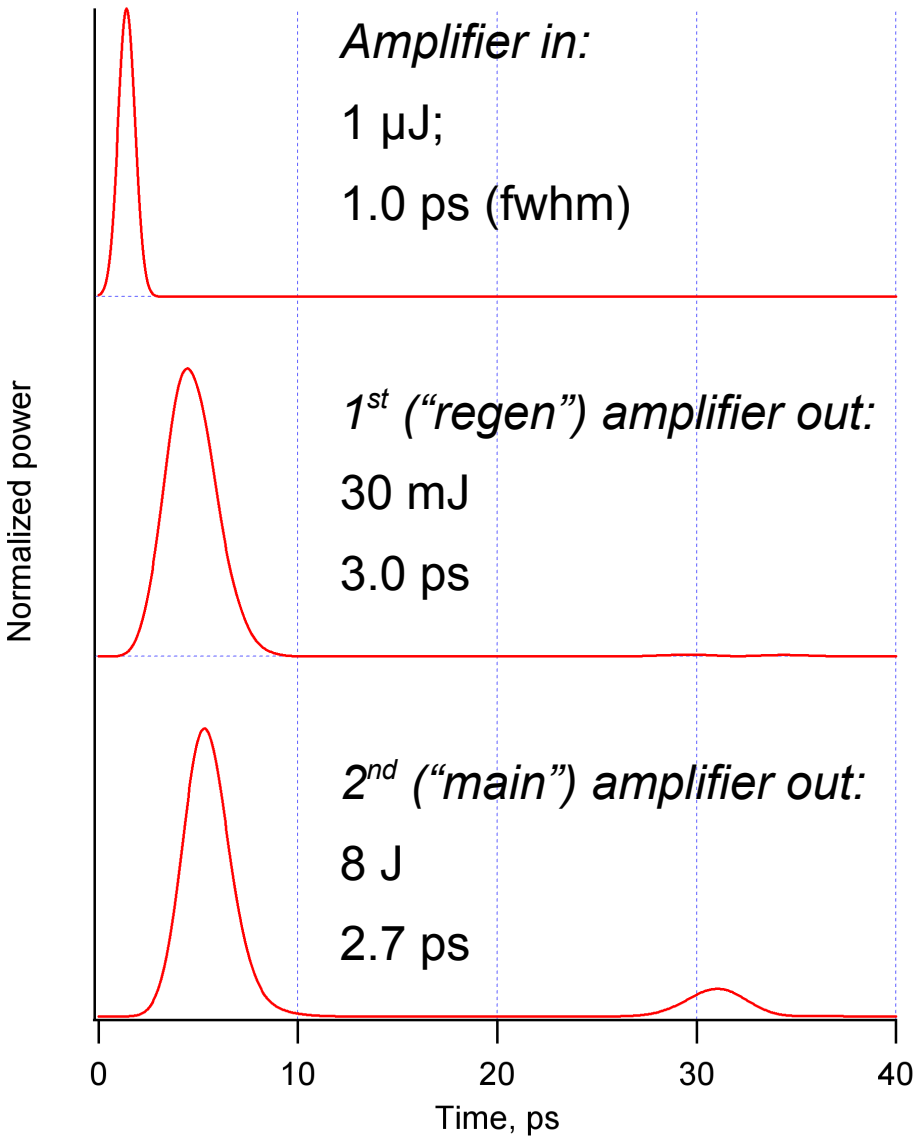
:(Complicated data analysis

Towards sub-picosecond: New pulse generation scheme





Towards sub-picosecond: Pulse stretching upon amplification



1st amplifier

10 atm; isotopic gas

12 passes

Losses: 15% / pass

2nd amplifier

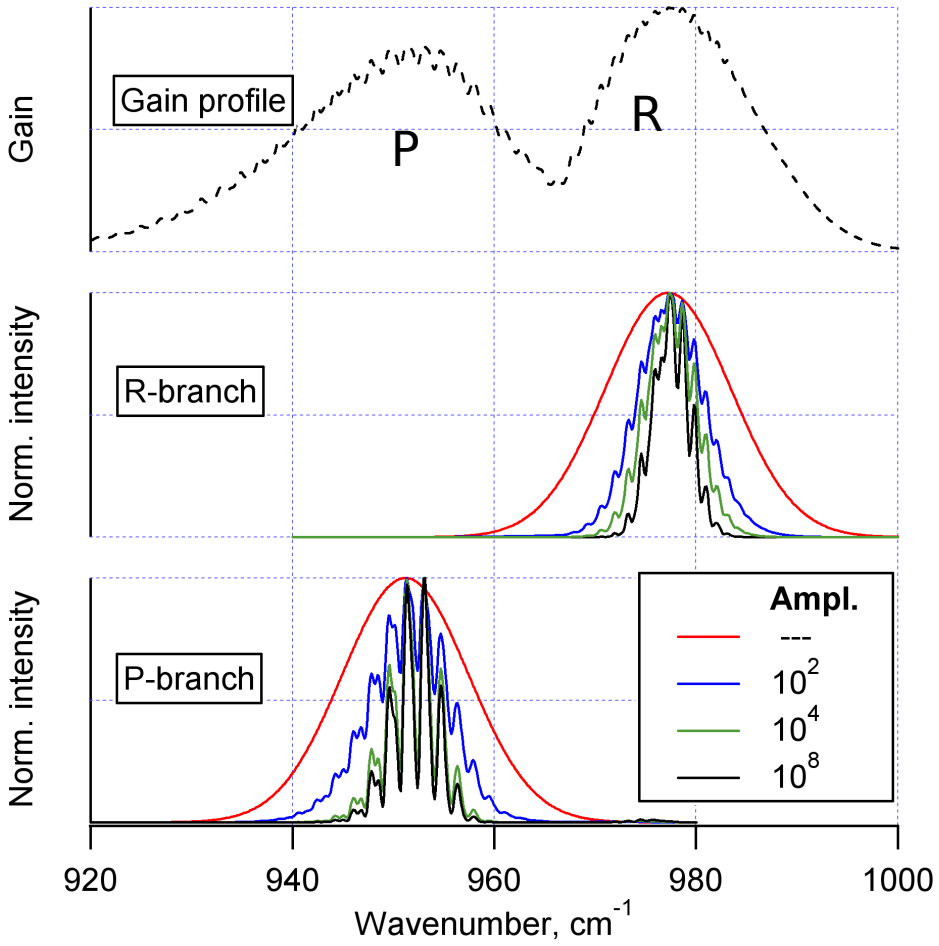
10 atm; regular gas

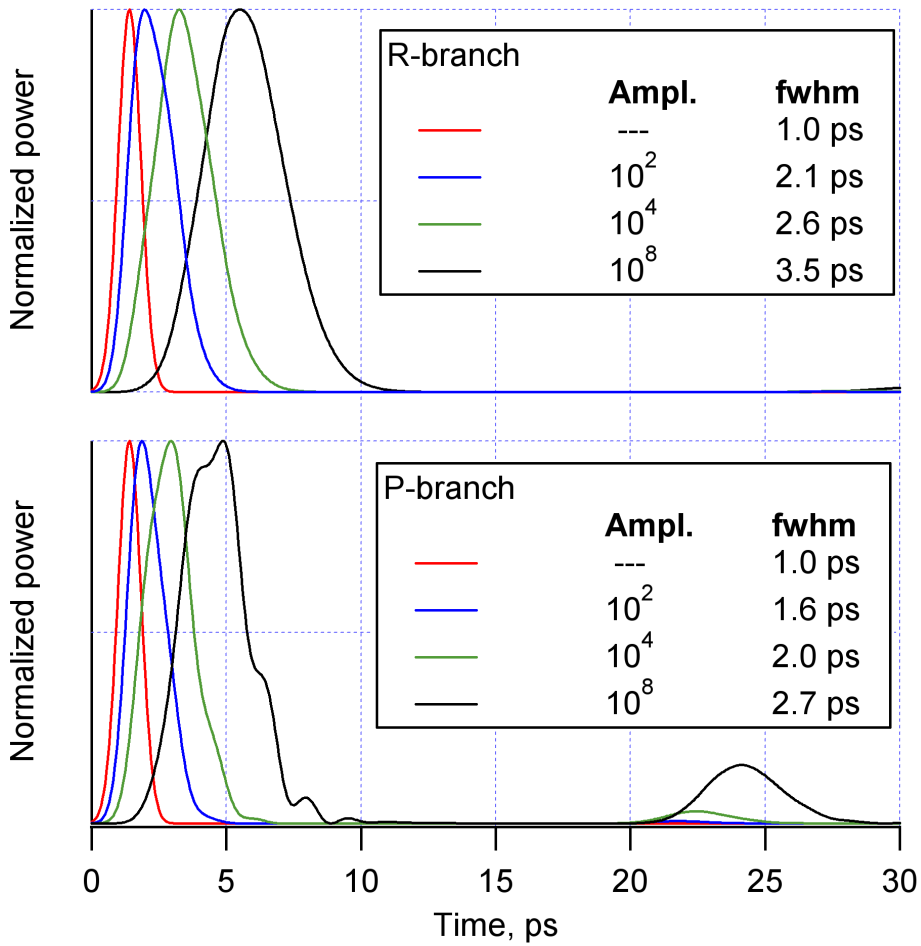
4 passes

Losses: 10% / pass

Towards sub-picosecond: Pulse stretching upon amplification

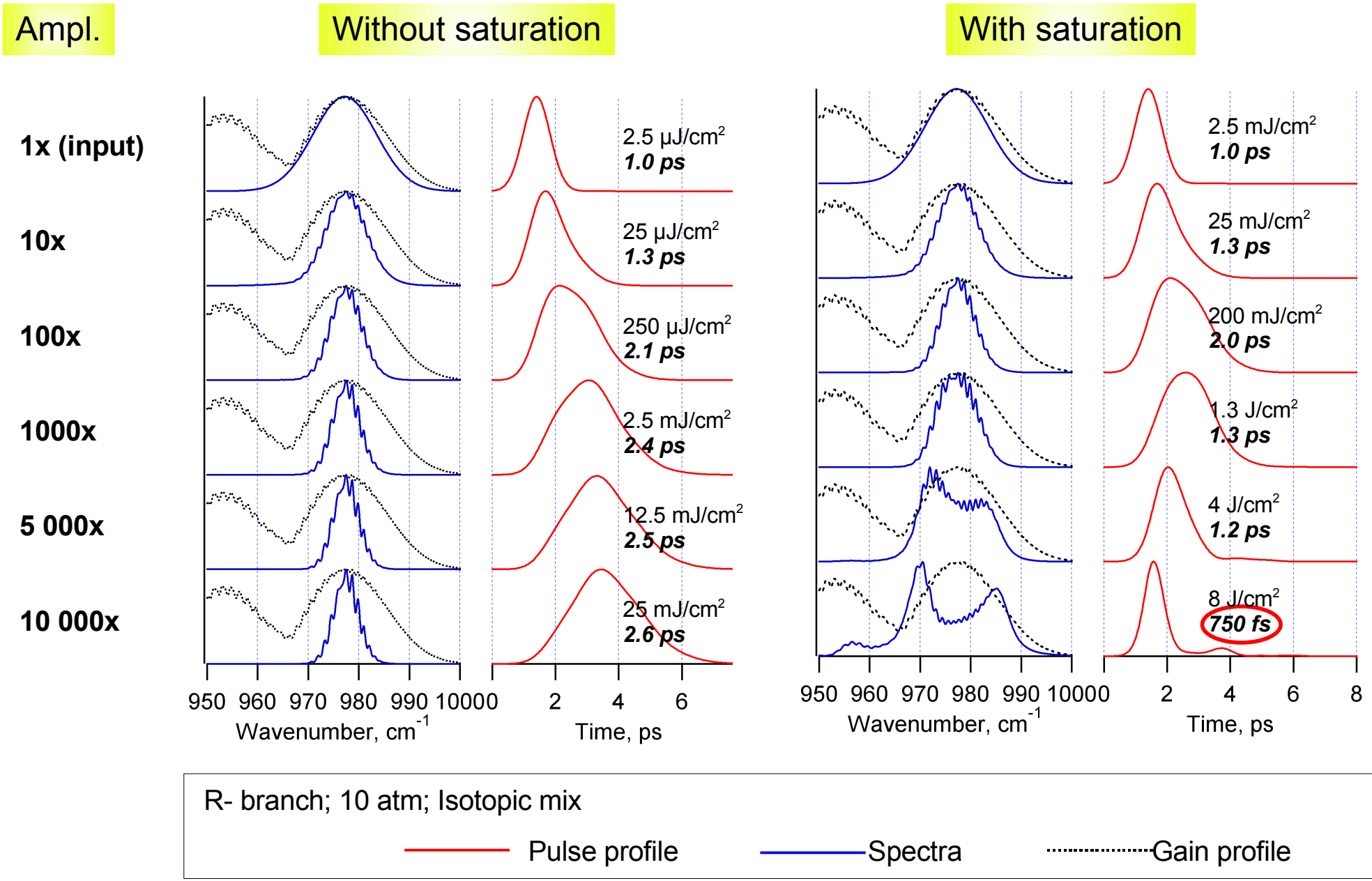
Picosecond pulse amplification: Spectrum narrowing => Pulse broadening



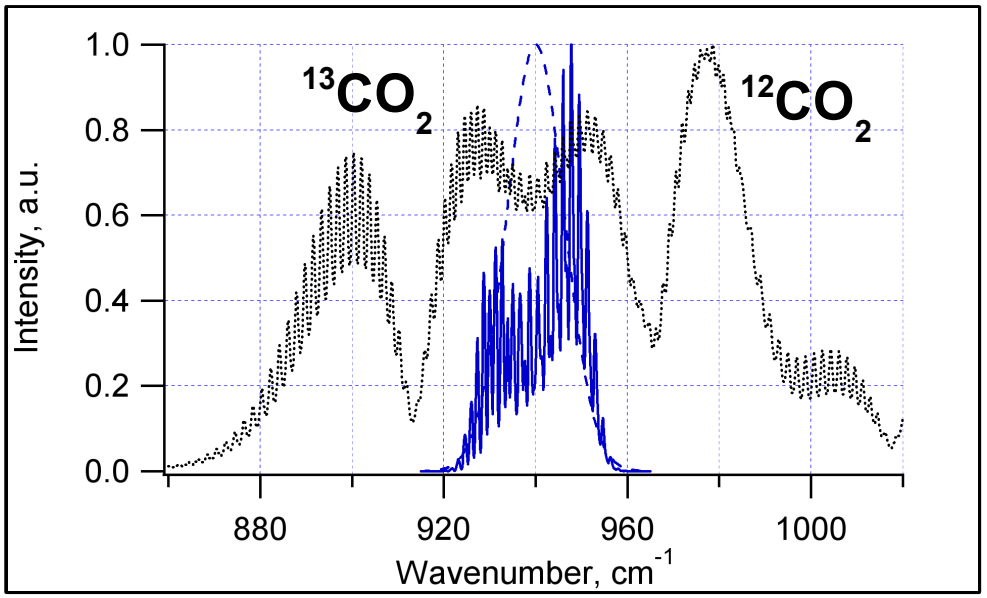


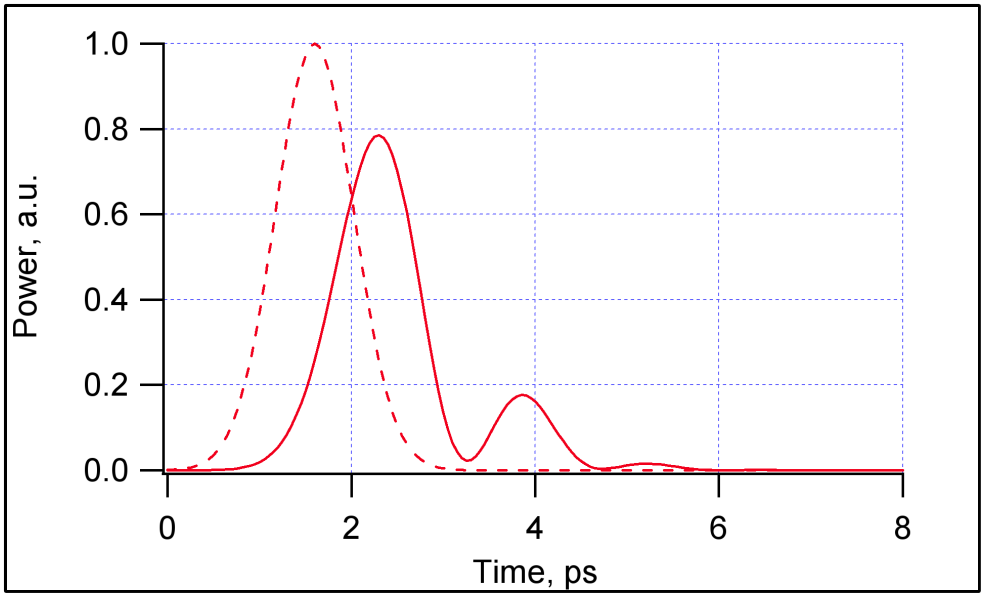
10 atm; Isotopic mix; Initial pulse: 1 ps (fwhm), 2.5 nJ/cm^2

Towards sub-picosecond: Using spectral saturation



Towards sub-picosecond: More isotopes: C-13





[O-16] : [O-18] = 1 : 1

[C-12] : [C-13] = 1 : 0.8

Total pressure: 10 atm.

Amplification: 10 000x

Gain

Spectra:

Input pulse

Amplified pulse

Time profile

Input pulse x 10 000

Amplified pulse

Diagnostics IV: System upgrade plan

- Energy: *On-line monitoring of pulse energy in multiple positions*
- Time structure: *Streak camera, spectrometer, interferometer, autocorrelator*
- Miscellaneous: *Automatic logging of measured data*

- Advanced computer program for simulation of short pulse amplification is developed
- Diagnostics tools for measuring (sub-) picosecond pulse duration and time profile are implemented
- Agreement between simulations and experiment is demonstrated
- Strategy for addressing pulse splitting problem is developed and it's implementation is started
- Problems and possible solutions of sub-picosecond pulse amplification are considered
- Complete monitoring system upgrade is in progress