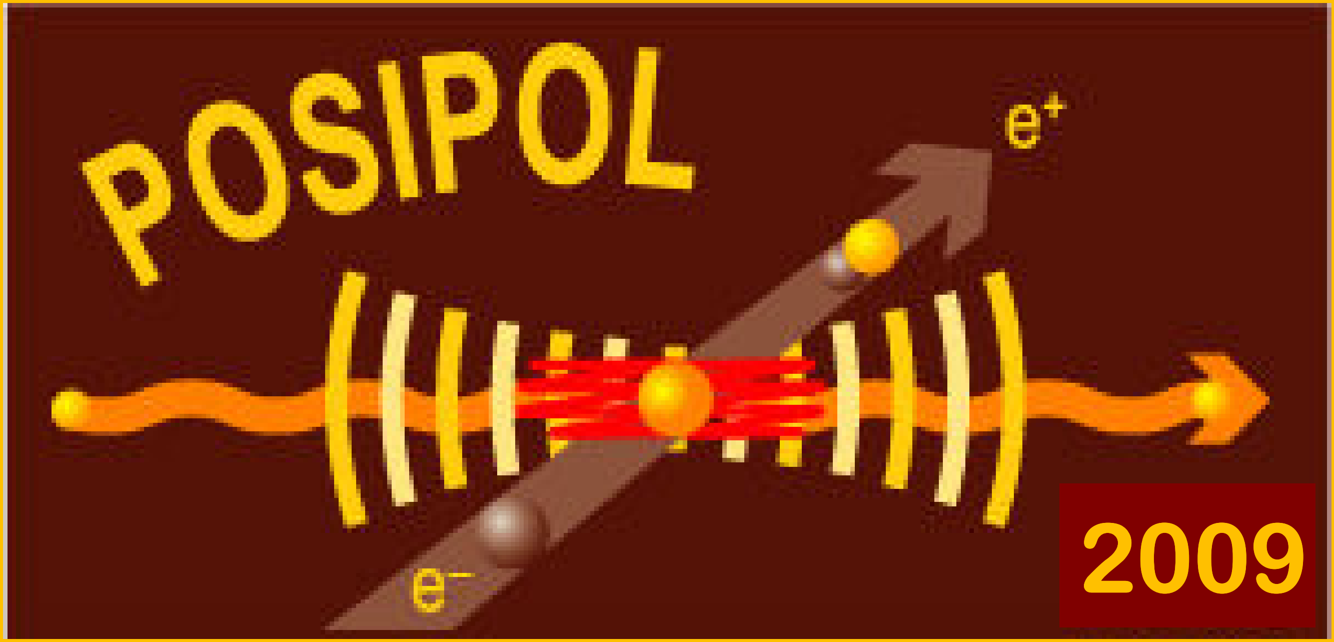


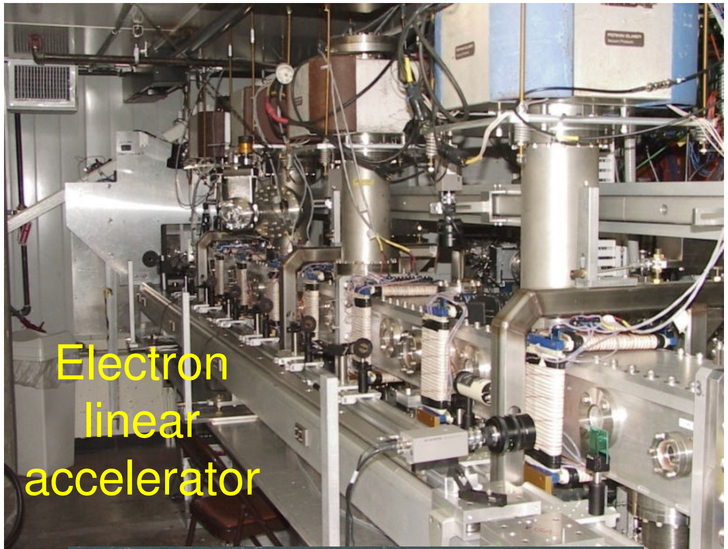
Polarized γ-source based on intra-cavity Compton backscattering (Compton LINAC scheme)

Igor Pogorelsky, Vitaly Yakimenko,
Mikhail Polyanskiy

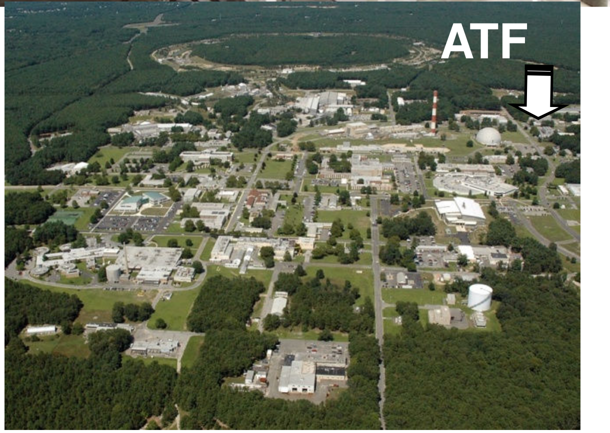
Brookhaven National Laboratory
Accelerator Test Facility

ATF @ BNL

Possibly the only user's facility that has both a relativistic e-beam and a powerful laser



Electron linear accelerator



ATF

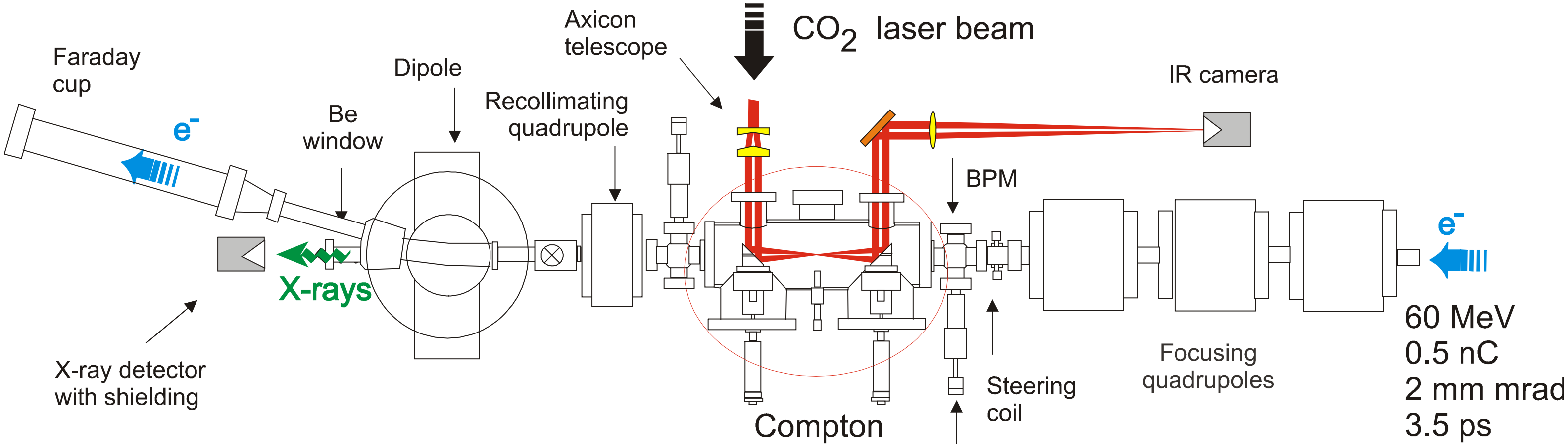
Ultrafast CO_2 laser system

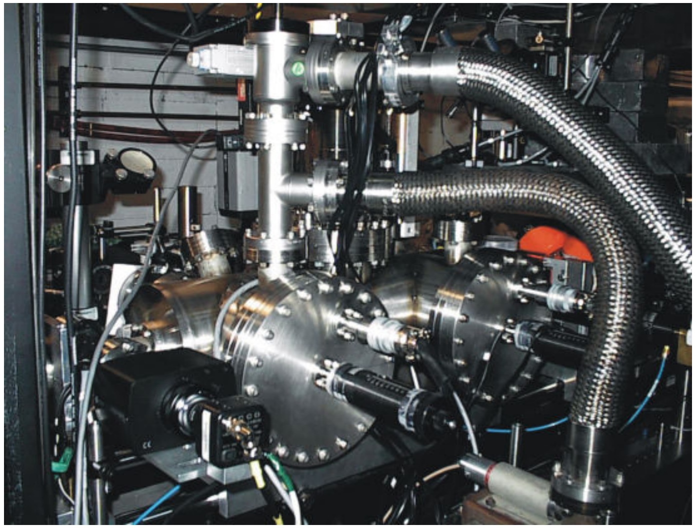
Slide 2

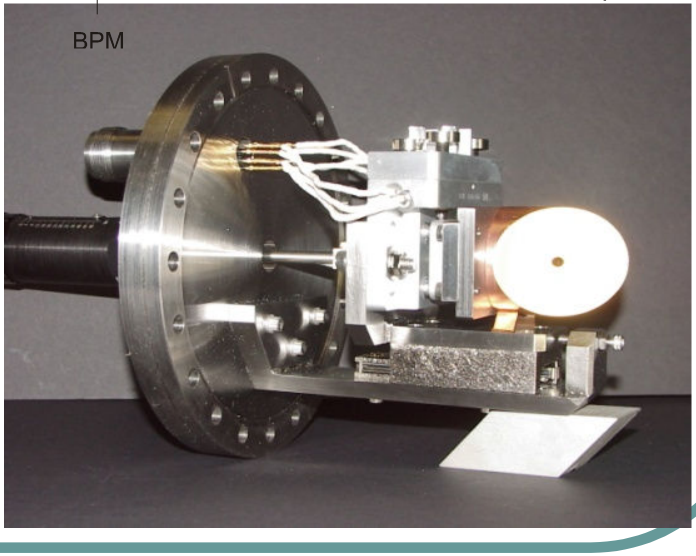
---

ip2 ...including BNL that opened a users facility for Advanced Accelerator studies 15 years ago. It is named ATF and equipped with a high-power CO2 laser a and 70-MeV electron linac to study interactions with electrons.
CO2 laser makes the biggest difference to compare with most of other facilities that are based on using ultrafast solid state lasers.
Igor Pogorelsky, 12/20/2008

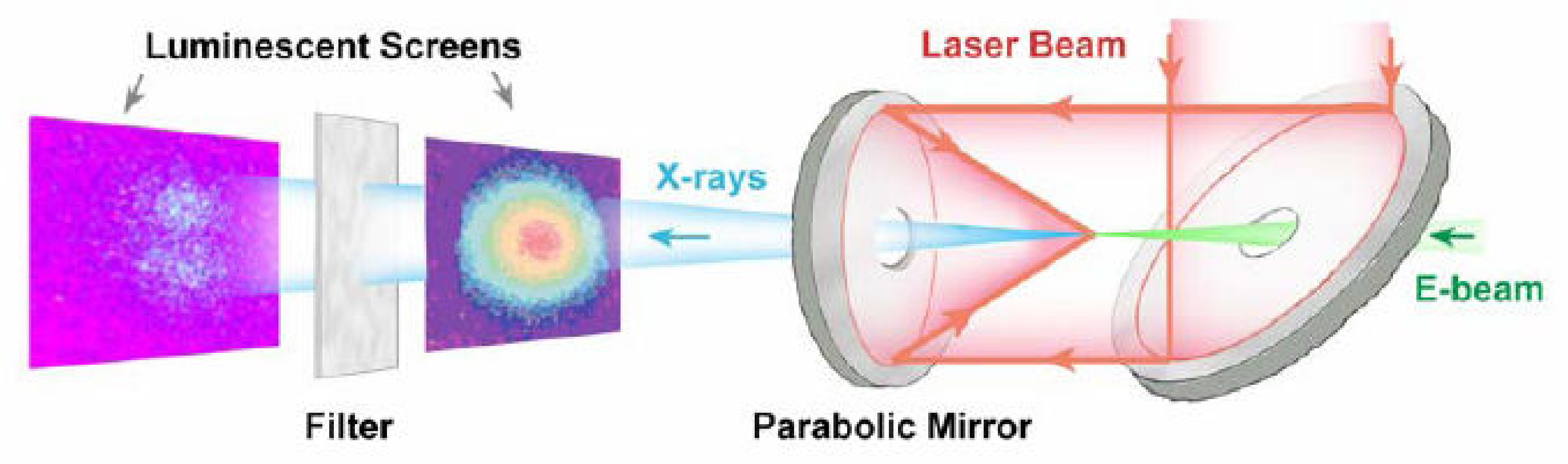
Prior art:
Thomson scattering experiment







Demonstrated: the record x-ray yield and the 2nd harmonic in relativistic Thomson scattering



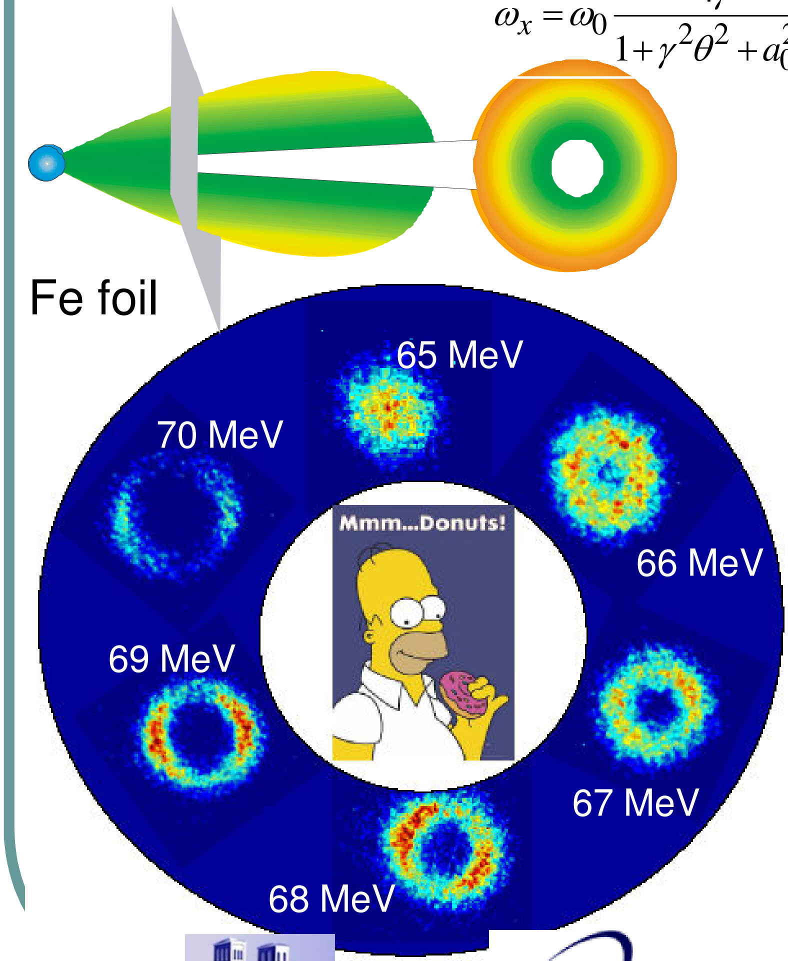
With 5 J CO_2 laser focused to $\sigma = 35\ \mu m$, we demonstrated record x-ray yield N_γ/N_{e-}~1 And 2nd harmonic in relativistic Thomson scattering

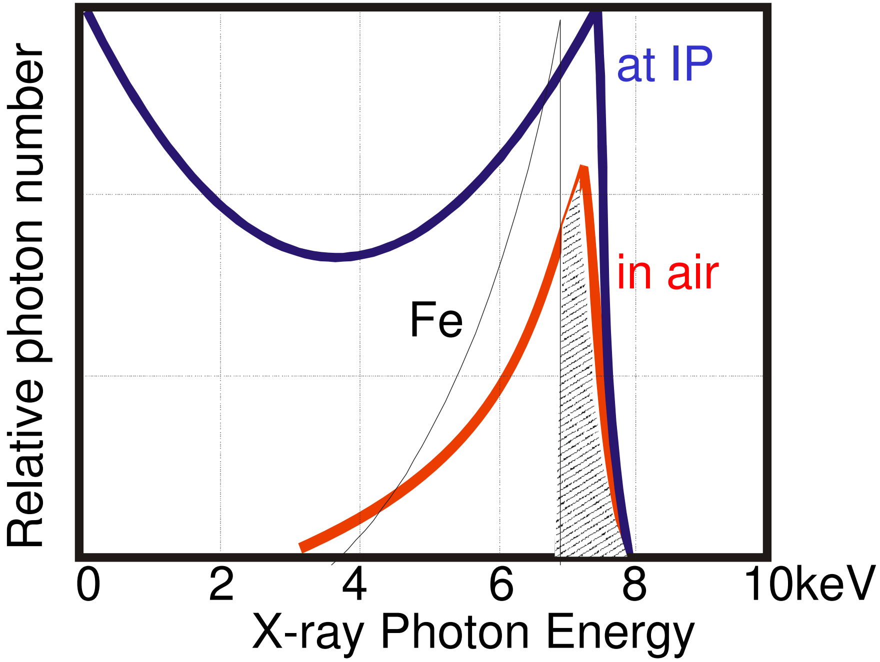
note that 10-μm laser produces 10 times more photons per Joule than 1-μm laser

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

K-edge allows to understand x-ray spectrum without spectrometer

$$\omega_x = \omega_0 \frac{4\gamma^2}{1+\gamma^2\theta^2 + a_0^2/2}$$

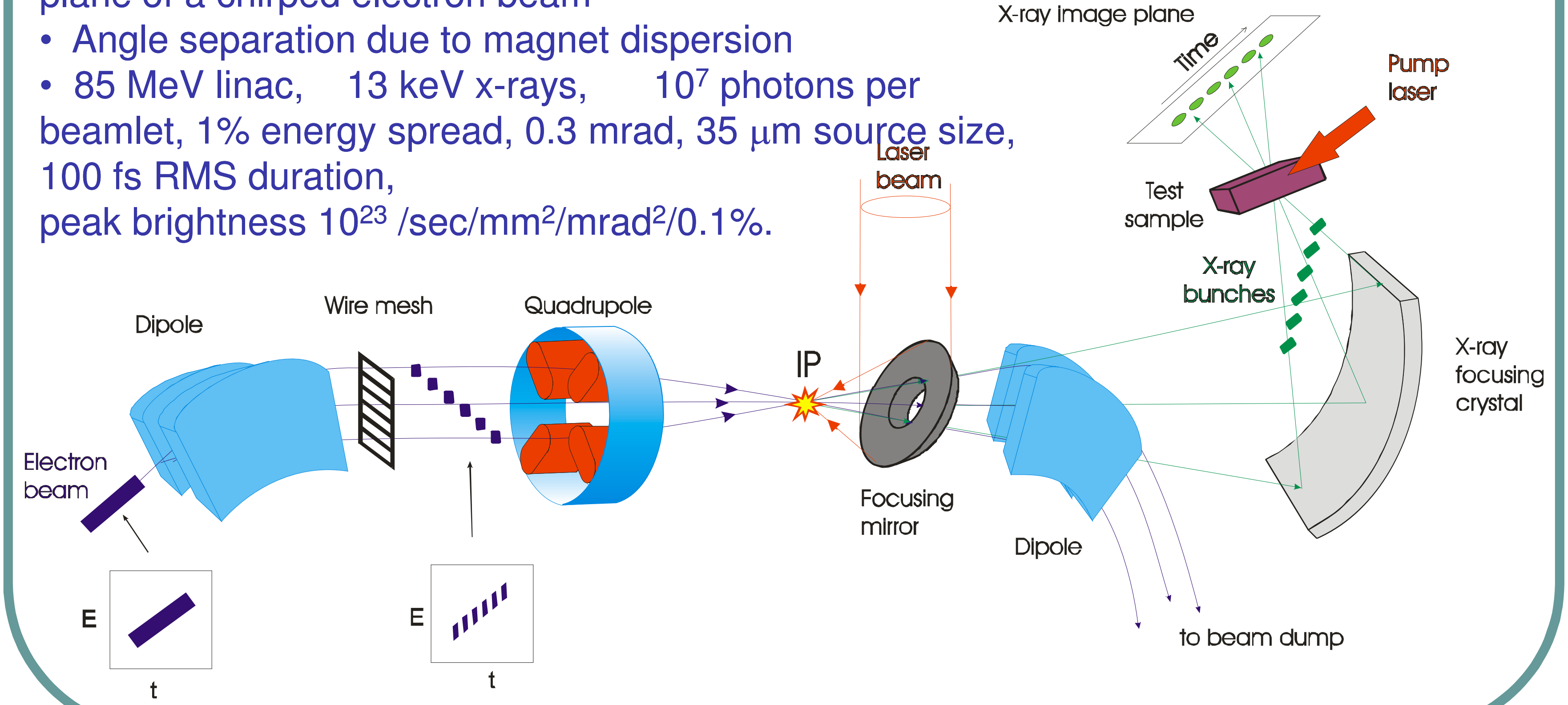




- Higher © => Higher E_x => More photons off-axis above K-edge => Bigger donut hole.
- Small energy spread is critical for high-contrast medical imaging (blood vessels).

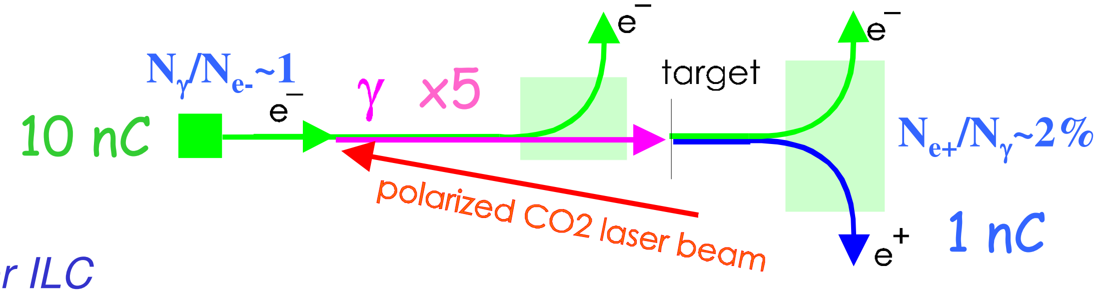
Ultra-fast x-ray "movie"

- Up to 10 x-ray images at 100 fs interval
- Time structure corresponds to electron micro-bunches
- Micro-bunches produced by a mask placed in energy plane of a chirped electron beam
- Angle separation due to magnet dispersion
- 85 MeV linac, 13 keV x-rays, 10^7 photons per beamlet, 1% energy spread, 0.3 mrad, 35 μm source size, 100 fs RMS duration, peak brightness 10^{23} /sec/mm²/mrad²/0.1%.



Direct electron-gamma–positron sequence (no stocking)

- The ILC and CLIC designs specify a 1 nC charge per each positron bunch.
- The conversion efficiency of the polarized γ-photons into polarized positrons is expected to be about 2%, optimized for the 60% level of the beam's polarization. Therefore, every positron requires, as precursors, 50 γ-photons assembled in the same format (bunch length and repetition rate) as the e^--e^+ collider beams.
- We propose to accumulate this γ-flux via Compton scattering at several consecutive IPs. In each IP, a 4.75-GeV *e*-beam undergoes a head-on collision with a CO_2-laser pulse that produces one γ-photon per electron.



example for ILC

Linac Compton Source for ILC (CLIC)

e- beam energy	4.75 GeV
e- bunch charge	10 (5) nC
RMS bunch length (laser & e^- beams)	3-5 ps
γ beam peak energy	40 MeV
Number of laser IPs	5 (10)
Total $N\gamma/Ne^-$ yield (in all IPs)	5 (10)
$Ne^+/N\gamma$ capture (@60% polarized)	2%
Ne^+/Ne^- yield	0.1 (0.2)
Total e^+ yield (@60% polarized)	1nC
# of stacking	No stacking

Choosing electron linac

- A train of low-emittance electron bunches will be produced with a photo-injector gun and a 4.75 GeV (γ~10^4) linear accelerator.
- We consider a 3-m-long SLAC-type accelerator module that provides the total acceleration

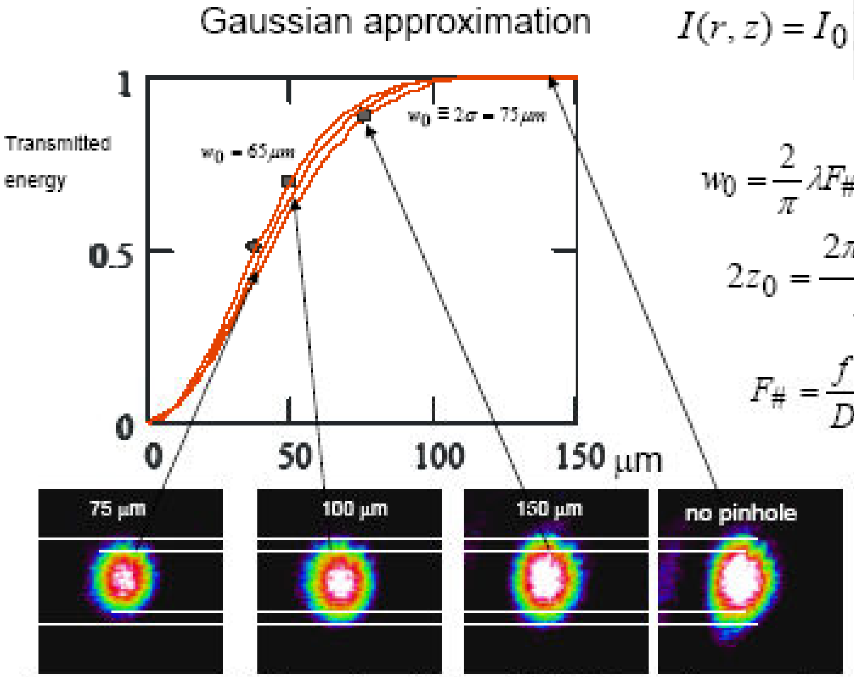
$$\boxed{\Delta E\,[\mathrm{MeV}] = 10.8 \times \sqrt{P_{\mathrm{RF}}[\mathrm{MW}]} - 39.5 \times I[\mathrm{A}]}$$

where P_{RF} is a klystron power and I is an equivalent steady-state current. A 65-MW klystron will produce a 18.5 MV/m loaded acceleration gradient for the 10 (5) nC bunch charge and a 12 (5) ns bunch spacing. Accordingly, a 250-m long linac would be required to generate a 4.75 GeV *e*-beam.

e-beam emittance and divergence

- Superconducting electron gun under development at BNL will be the exact match to ILC and CLIC .
- The normalized emittance is expected to be 5÷10 μm.
- The focusing system for the *e*-beam would need to generate one with a beta-function of ~1 m that would entail beam sizes of σ=30 μm in the middle of the waist, and 50 μm at the ends of the ~2.5-meter-long total interaction region that extends over 5 -10 IPs.
- A 4.75-GeV *e*-beam divergence will be 3 times smaller than $1/\gamma$.
- Simultaneously, a CO_2 laser spot size with $2\sigma \equiv w_O = 70$ μm can be realized as was demonstrated experimentally.

Characterizing laser focus

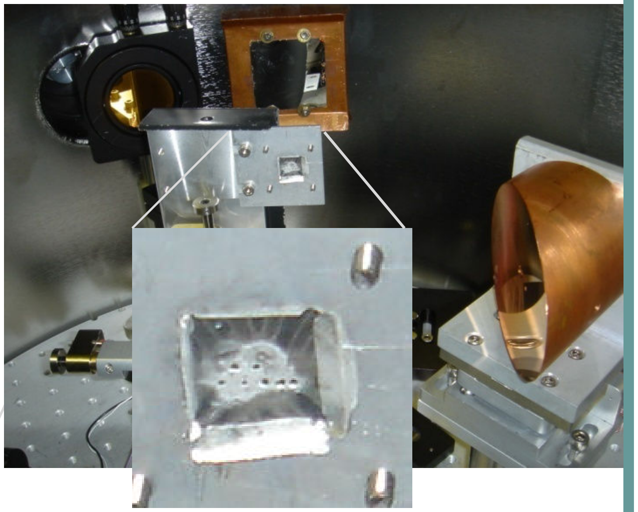


$$I(r,z) = I_0\left[\frac{w_0}{w(z)}\right]^2 \exp\left[-\frac{2r^2}{w^2(z)}\right]$$

$$w_0 = \frac{2}{\pi}\lambda F_{\#}M^2$$

$$2z_0 = \frac{2\pi w_0^2}{\lambda}$$

$$F_{\#} = \frac{f}{D}$$



Laser focus transmitted through pinholes of 75-150 μm dia imaged on IR camera.

Gaussian approximation with w_0=65 μm is the best fit to the observed transmission through pinholes.
For ideal diffraction-limited beam, such focus corresponds to $F_{\#}$=10 and double Rayleigh distance 2.5 mm.
Instead, we measure $2z_0$=0.8 mm and $F_{\#}$=4. This means that the beam has M^2=1.6.

Conclusions:

- Laser intensity 10^{16} W/cm^2,
- Target position shall be controlled with 100-200 μm accuracy.

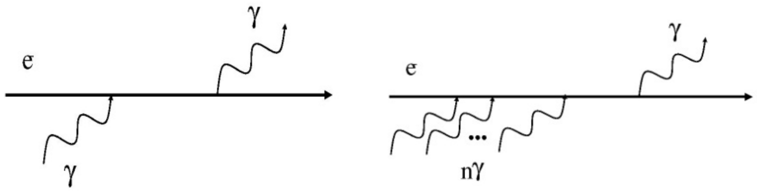
Selecting CO_2 laser

- The integral efficiency of the γ-production in the head-on collision can be estimated from $\boxed{N_\gamma / N_e = N_\phi \times \sigma_c / S}$

  where N_γ, N_e, and N_ϕ are the numbers of γ-rays, electrons, and laser photons, S is the cross-section area of the interacting beams, and σ_c is the Compton scattering cross-section.
- For idealized flat beams of 70 μm diameter, the condition N_γ/N_e=1 is satisfied at the corresponding CO_2-laser or SSL energy of 1 J and 10 J.
- Estimating the proportion of N_γ/N_e for more realistic Gaussian beams would require transverse- and longitudinal-integration over the IP space that still might leave open the question about the accuracy of a Gaussian approximation for spatial- and temporal-distributions in realistically achievable beams.
- Instead, we have produced already an experimental verification of reaching the condition N_γ/N_e =1.

Stay below nonlinear scattering!

- Overall cost of the CPPS will be dominated by the *e*-beam accelerator. Thus, it seams desirable to push the laser's power to its practical limits, so attaining maximum N_γ/N_e yields.
- However, such a trend ultimately might bring us into a regime of nonlinear Compton scattering



- Harmonics would be radiated at different wavelengths, and partially outside the solid cone of the γ-beam wherein the polarized positrons are produced.
- This might lower the efficiency of utilization of laser energy, and result in unproductive consumption of the *e*-beam's energy.
- Contribution of a nonlinear process is characterized by the normalized vector potential, a.

$$a = \frac{e}{m_e c^2}\sqrt{-<A_\mu A^\mu>}$$

$$= 0.60\times10^{-9}\cdot\lambda[\mu\mathrm{m}]\cdot I^{1/2}[\mathrm{W/cm}^2]$$

Nonlinear process is pronounced at $a\sim 1$.

Optimization of laser parameters

- Maximum efficiency of the laser and *e*-beam interactions is achieved when the laser's focal spot matches the *e*-beam's size and its pulse length should be close to the Rayleigh length ,

$$\boxed{R_L = \pi w_o^2 / \lambda}$$

- For a Gaussian beam with w_O=70 μm (FWHM 100 μm), $R_L \approx 1.5$ mm,
- To fit into R_L, the optimum laser pulse length is $\tau = 5$ ps,
- and the limiting condition a=1 is attained for CO_2 laser at $P = 1$ TW and $E = 5$ J.
- We choose a<0.5, E=1-2 J

CO_2 laser beam parameters at the Compton IP

Normalized vector potential	a_0	0.5
Focus size	$2\sigma_L = w_0$	70 μm
Rayleigh length	R_L	1.5 mm
Pulse length	τ_L	5 ps
Pulse energy	E_L	1 J
γ-ray production efficiency	N_γ / N_e	~1

E-beam and Laser temporal format for ILC and CLIC

- Depends upon the collider's design matrix which is subject to frequent changes.
- One proposed ILC design suggests generating 100 bunches spaced by 12 ns that form a 1.2-μs trains with the 150 Hz train repetition rate. We will use this as the basic design matrix to choose the laser and linac regimes.
- The original ILC design called for trains of ~3000 pulses with a 300 ns interval, and a 5 Hz train repetition rate, thus maintaining the same total number of 15,000 bunches. Such format is not practical for pulsed CO_2 lasers or for high-average-current linacs.
- The 150 Hz format can be converted to 5 Hz by accumulating 3000 positron bunches in the dumping ring, so forming an injection beam.
- Other desirable matrix, such as CLIC's 312 pulses, 0.5 ns interval, 50 Hz, can be accommodated by adjusting the laser/linac and dumping ring formats.

ILC and CLIC requirements

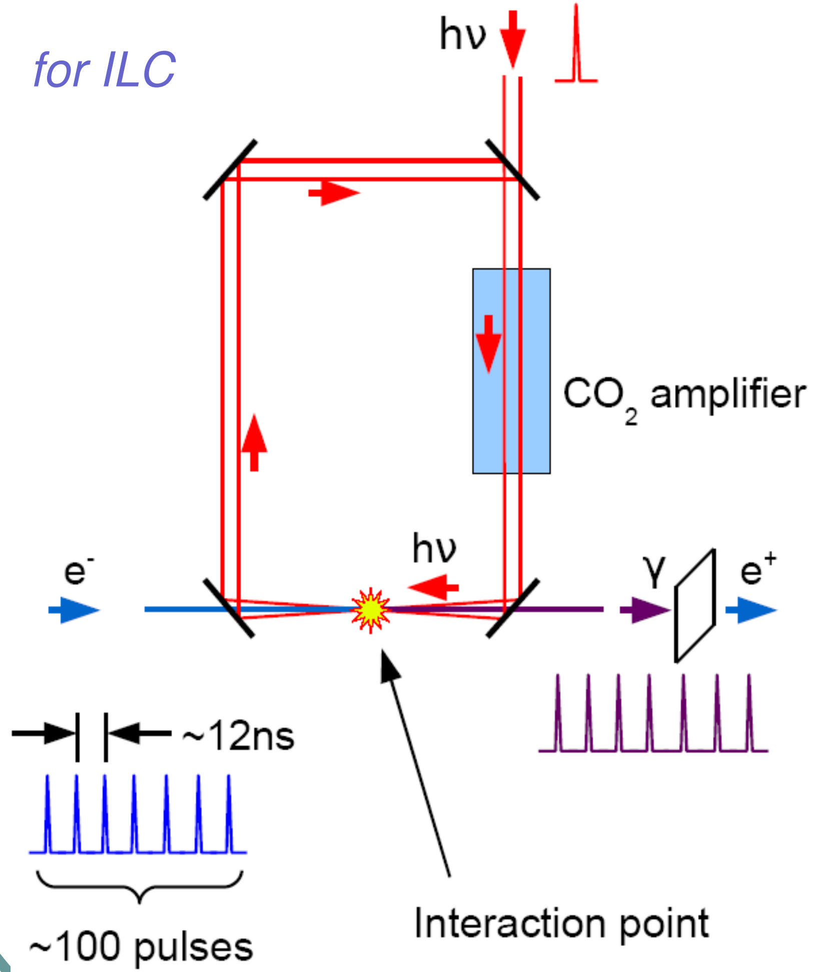
	ILC	CLIC
Pulse repetition rate	150 *Hz*	50 *Hz*
Bunches per pulse	100	312
Bunch Spacing	12 *ns*	0.5 *ns*
e^+ bunch	1 nC	1 nC
Laser energy	1 *J*	1 *J*
Laser pulse length	5 *ps*	5 *ps*
Number of lasers (IPs)	5	10

•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 IP.

Concept of a high-repetition e^+-source

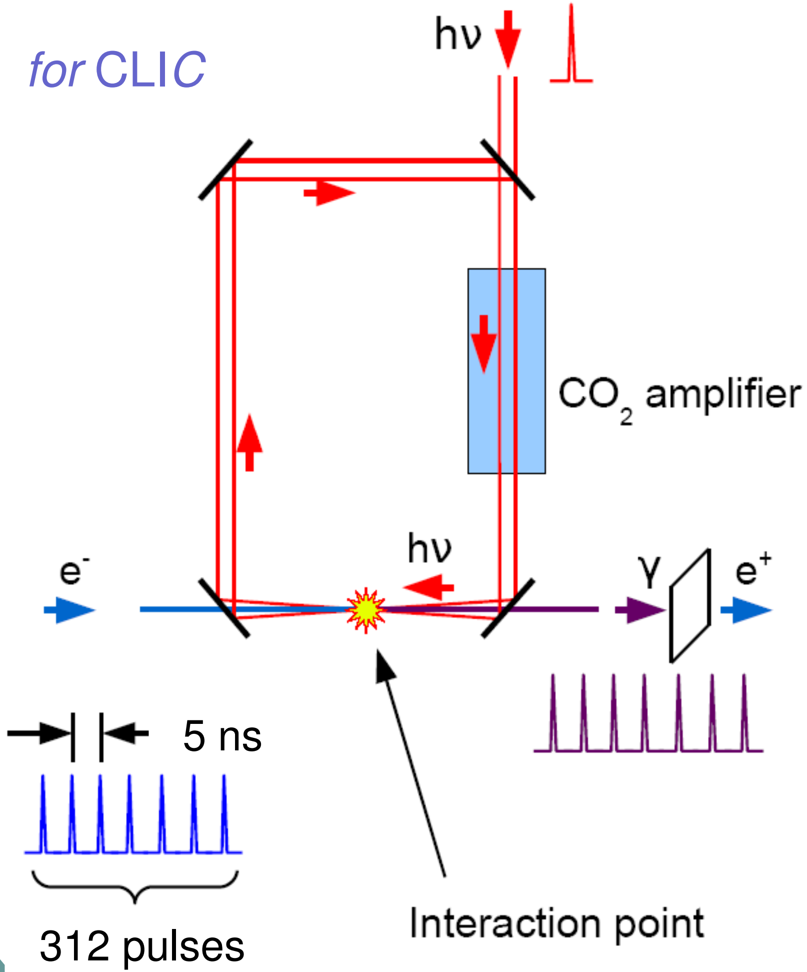
for ILC



- V. Yakimenko and I. Pogorelsky, Phys. Rev. ST Accel. Beams **9**, 091001 (2006) .
- We propose to multiply the Compton γ-source repetition rate by placing it inside the laser 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.

Concept of a high-repetition e^+-source

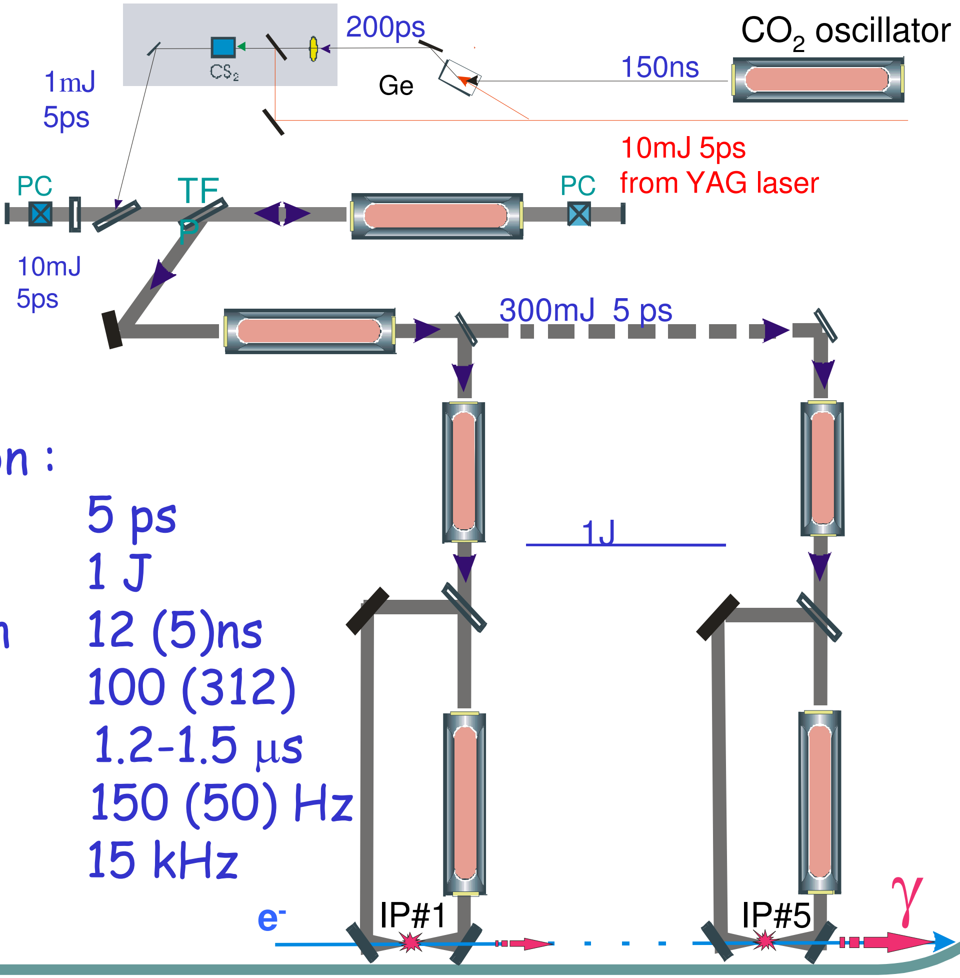
for CLIC



- •V. Yakimenko and I. Pogorelsky, Phys. Rev. ST Accel. Beams **9**, 091001 (2006) .
- •We propose to multiply the Compton γ-source repetition rate by placing it inside the laser 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.
- •For CLIC need reformatting to 0.5 ns in a damping ring.

Proposed CO_2 Laser system

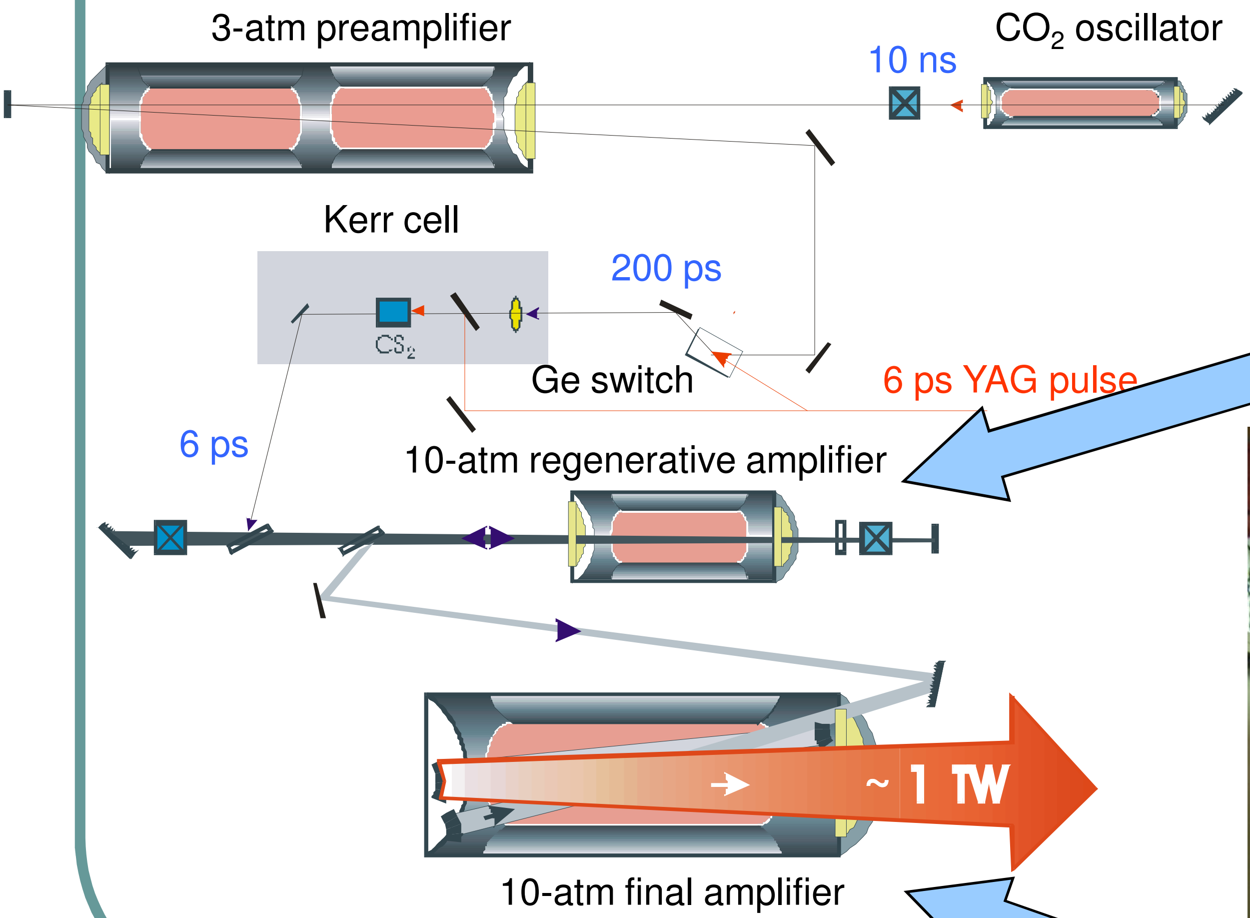
- production of 5-ps seed pulses
- amplification in regenerative amplifier
- power amplification to the level 1J/pulse

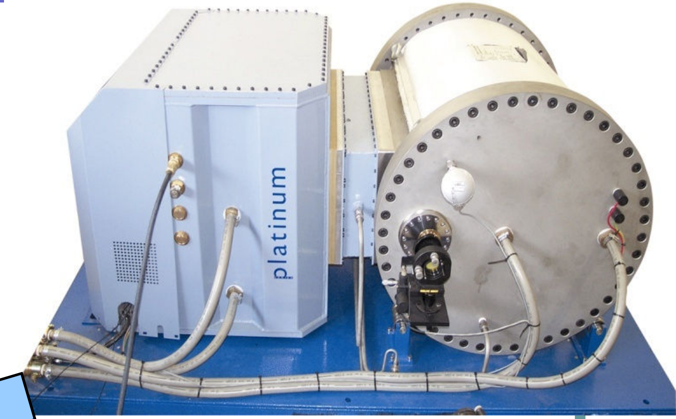


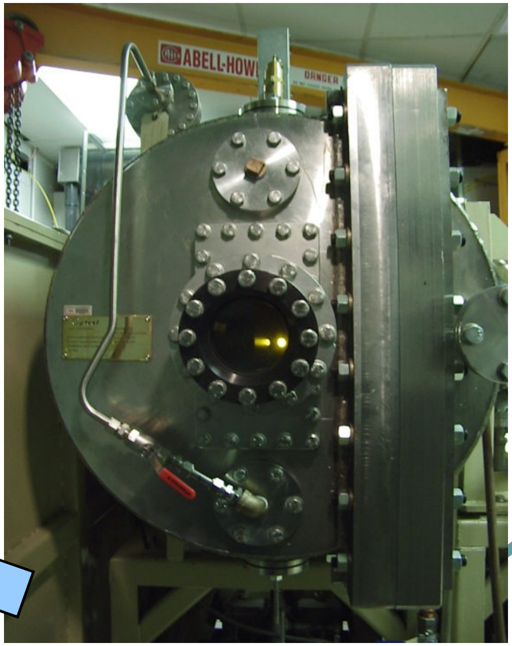
- intra-cavity pulse circulation :

pulse length	5 ps
pulse energy	1 J
period inside pulse train	12 (5)ns
circulations per shot	100 (312)
total train duration	1.2-1.5 μs
train repetition rate	150 (50) Hz
cumulative rep. rate	15 kHz

BNL/ATF CO_2 laser system





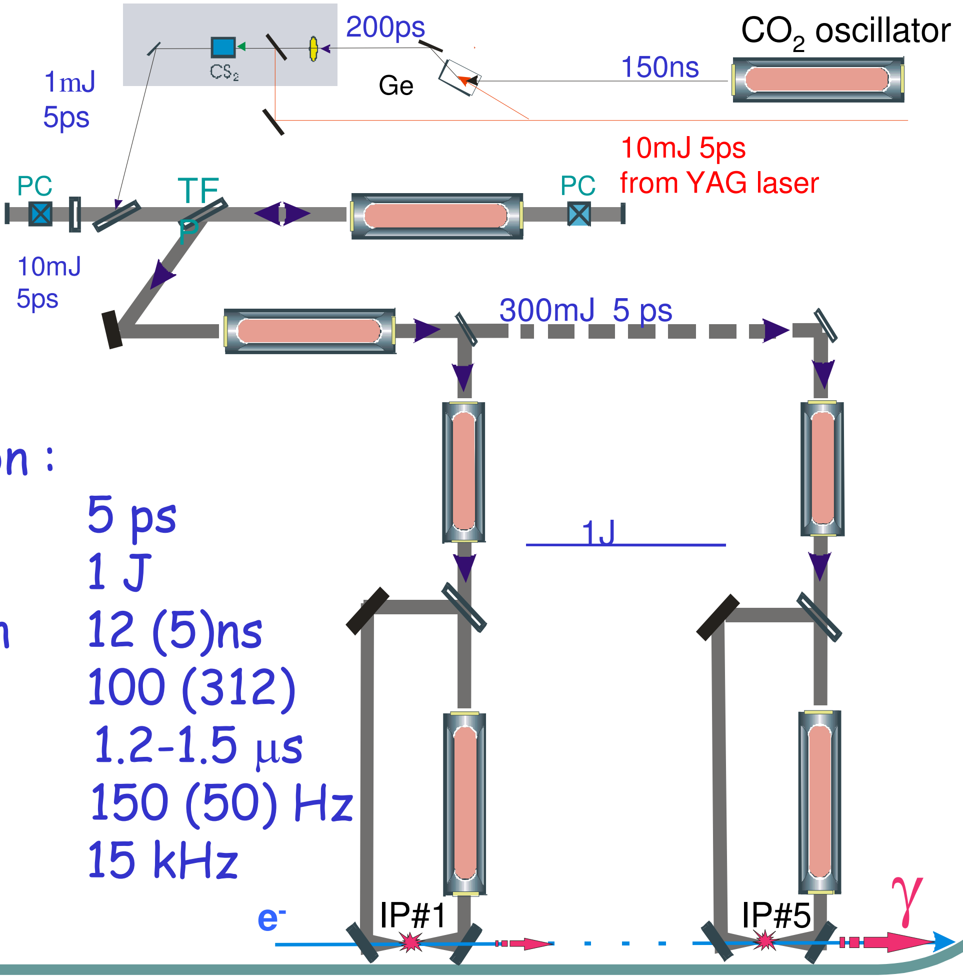


Slide 21

ip3 This is a diagram of the ATF laser system.
A ps seed pulse is produced by a combination of two methods that i described previously- semiconductor switching and Kerr effect. Both controlled by YAG pulse and minimal pulse duration is limited by the available YAG. Two switches are used to improve a contrast of a seed pulse.
Low-pressure preamplifier serves to increase the initial peak power for a seed pulse to compete with noice build-up in the regenerative amplifier. The number of passes in regen is controlled by Pockels cells that trap a seed pulse inside and eject it before it reaches the optical damage energy that is about 50 mJ for small-aperture optics of the regen.
We use S. African SDI lasers for the oscillator and regen and Russian-build lasers for preamplifier and the final multi-pass amplifier that presently delivers about 0.5 TW peak power structured pulses. I gave this laser name PITER that stands for picosecond terawatt. Actually, it is built in Petersburg too. We have plans to upgrade this system to multi-TW as I will speak a little later...
You may notice that the laser system looks relatively simple. Low nonlinearities in gas lasers allow to amplify a picosecond pulse without chirping, stretching and compression nesessary for solid sate lasers. You just build your amplifier system in stages. Each stage is capable to severqal hundred and even thousand times amplification. Is this a limit or can we add another stage and bring the power to PW? From the first glance we already approached a technology limit in scaling the 10-atm laser. There will be a huge problem with a discharge and optics for a much-bigger-aperture laser of such a pressure. Isotopes provide some relief. But it will require Hudreds thousand $$ to fill a big machine with isotopes...
Igor Pogorelsky, 12/22/2008

Proposed CO$_2$ Laser system

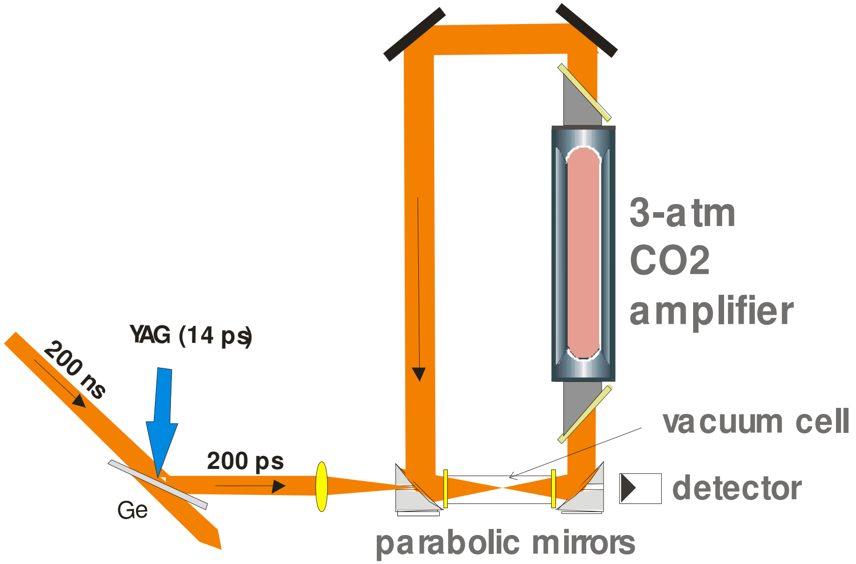
- production of 5-ps seed pulses
- amplification in regenerative amplifier
- power amplification to the level 1J/pulse

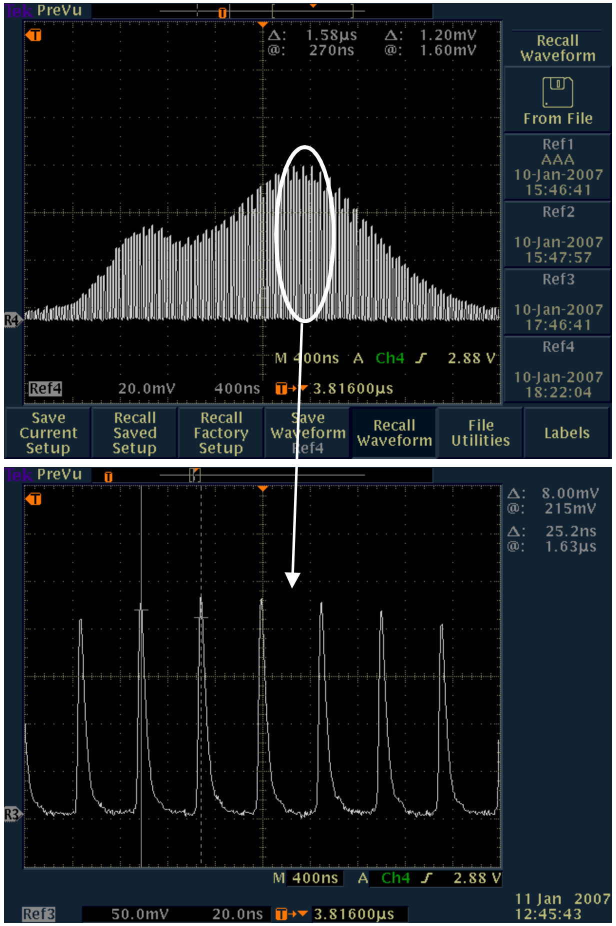


- intra-cavity pulse circulation :

pulse length	5 ps
pulse energy	1 J
period inside pulse train	12 (5)ns
circulations per shot	100 (312)
total train duration	1.2-1.5 μs
train repetition rate	150 (50) Hz
cumulative rep. rate	15 kHz

Test setup

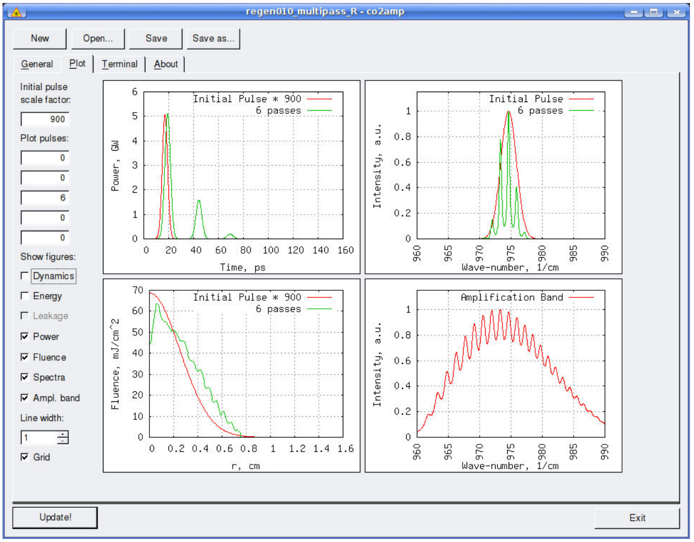




Single pulse circulation during 4 μs

Computer simulations

- *Based on numerical solution of* *Maxwell-Bloch* *equations*
- *Accurate* *molecular dynamics* *simulation*
- *Realistic pumping* *model*
- *Beam propagation* *algorithm based on diffraction theory*



Initial pulse scale factor: 900

Plot pulses: 0, 0, 6, 0, 0

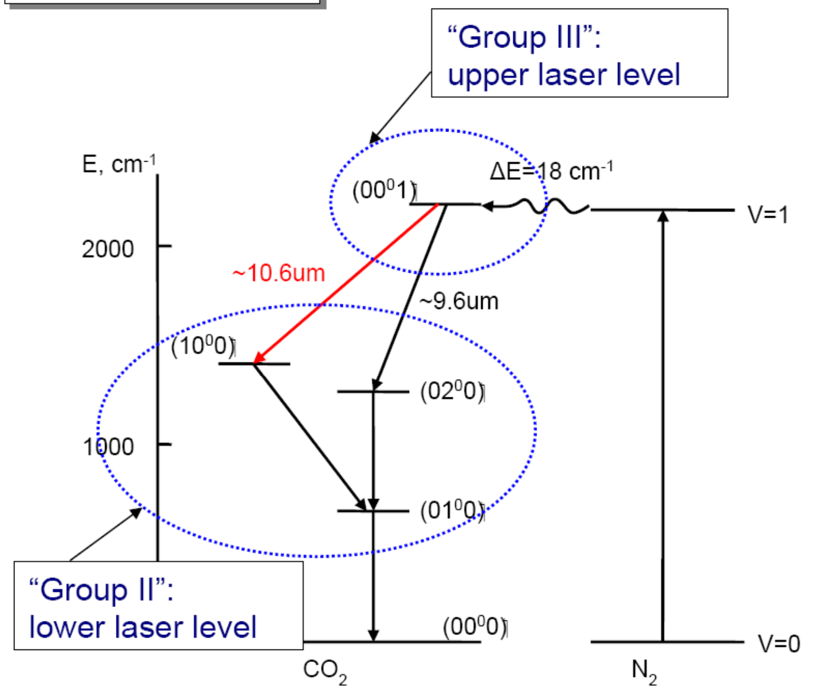
Show figures:

☐ Dynamics
☐ Energy
☐ Leakage
☑ Power
☑ Fluence
☑ Spectra
☑ Ampl. band

Line width: 1

☑ Grid

Relaxation dynamics



Gas	k_2, torr^{-1}s^{-1}	k_3, torr^{-1}s^{-1}
CO_2	194	350
N_2	650	106
He	3270	85

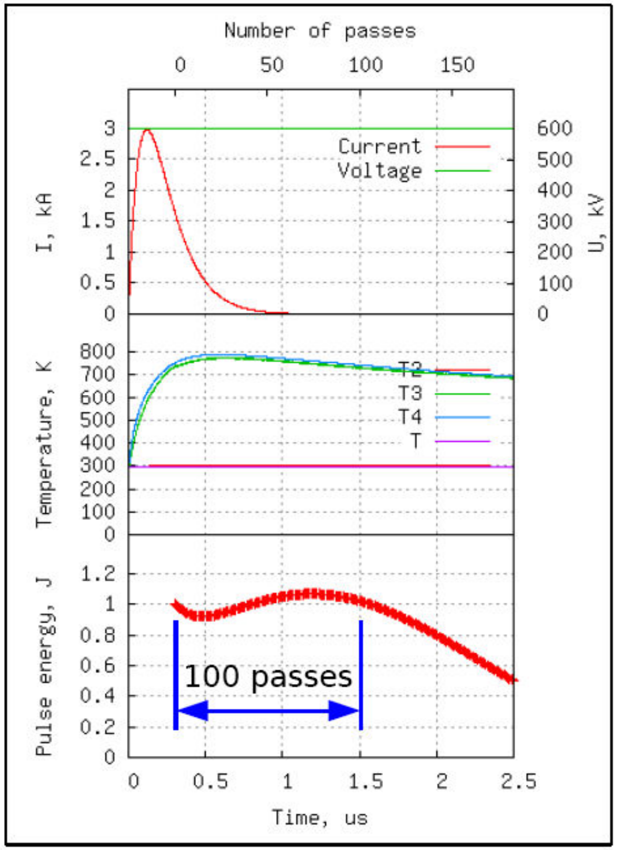
$k_2 = k_2(T)$, $k_3 = k_3(T)$!

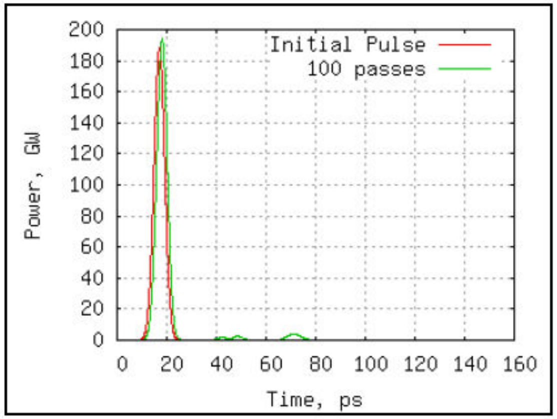
T = 300K

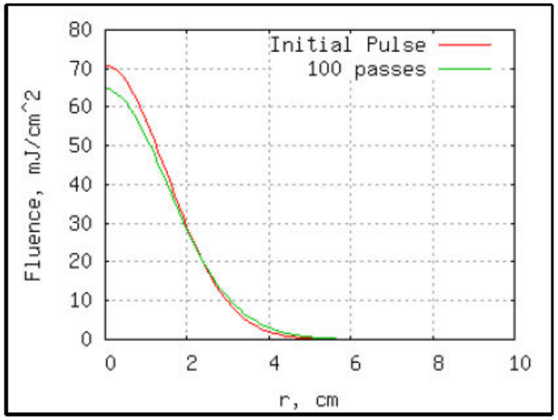
Computer simulations

multipass dynamics

- Pressure:
  - 5atm
- Pulse energy:
  - 1J
- Pulse length:
  - 5ps
- Roundtrip time:
  - 12ns
- Wavelength:
  - 10.2µm (10R)
- Optical losses:
  - 5% / pass
- Gas mixture:
  - 0.5 : 3 : 6.5
- Isotopes:
  - $[O^{16}] : [O^{18}] = 0.8 : 1$

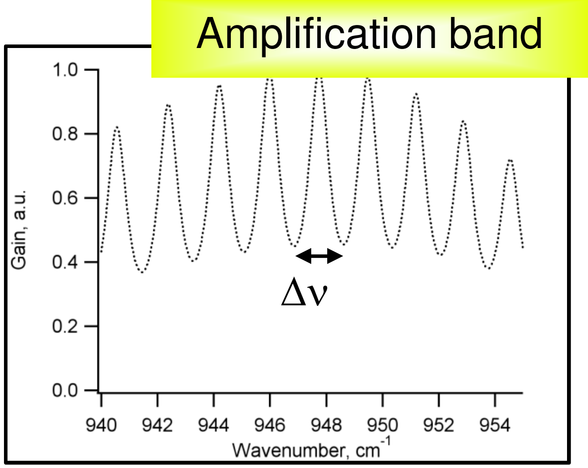






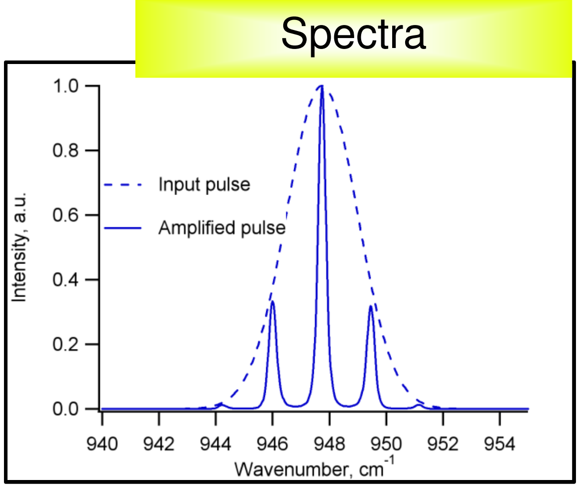
Compare simulations 10 atm regular 5 atm isotopes, gain, stored energy

Pulse splitting problem


Amplification band

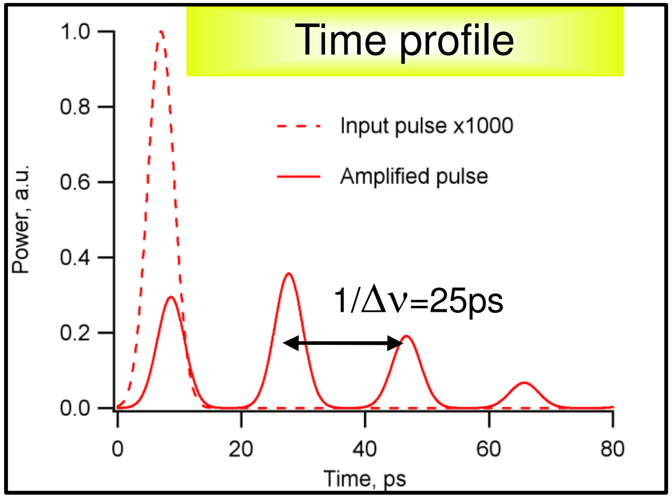
Case shown:

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


Spectra

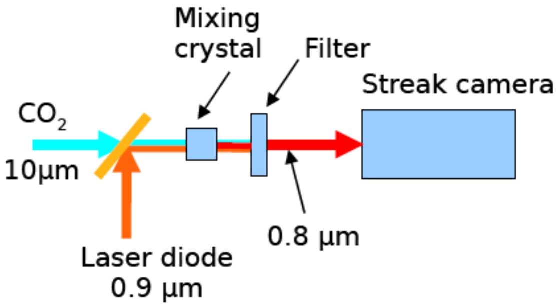
Fourier

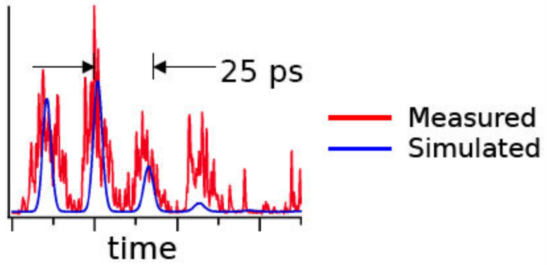
transform.


Time profile

Pulse diagnostics

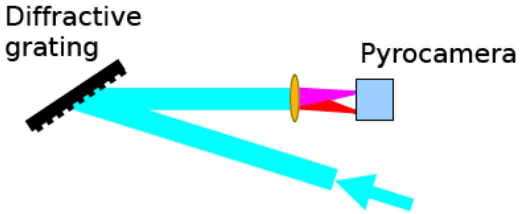
"Streak camera"

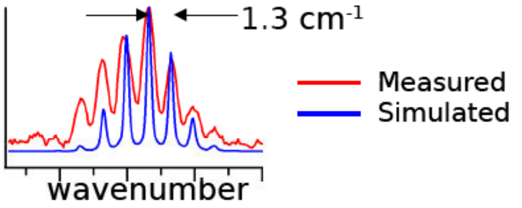




- :) Single-shot
- :(Low resolution (~10 ps)
- :) Train measurements

"Spectrometer"





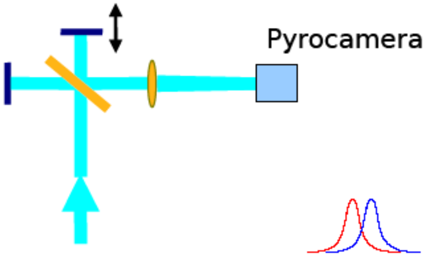
Fourier transform

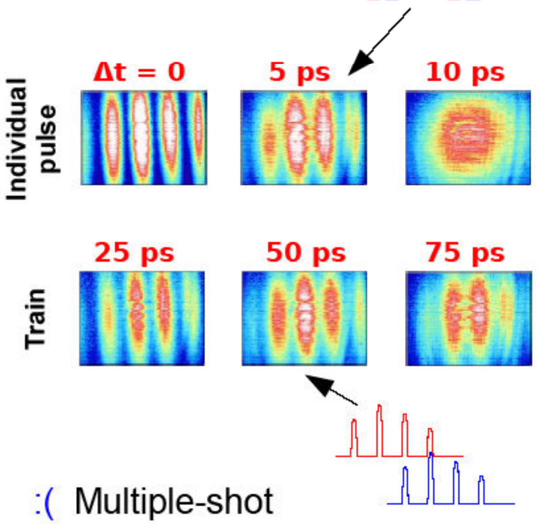
Total bandwidth <=> Individual pulse
sub-ps resolution

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

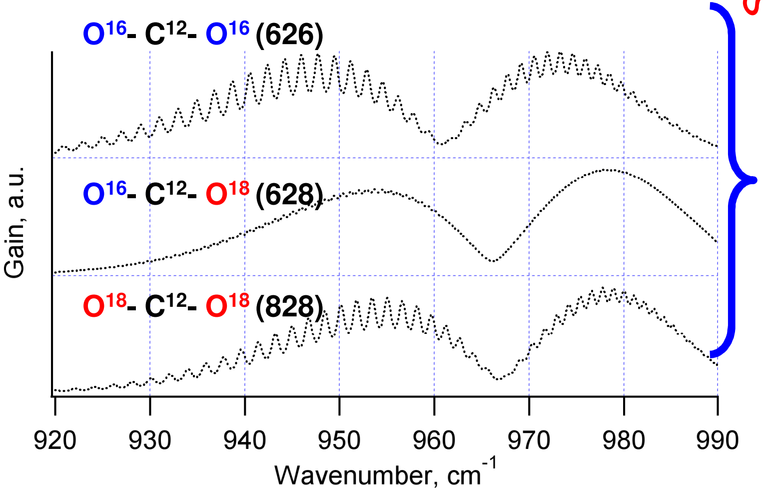
Addressing pulse splitting: "smoothing" of gain spectrum

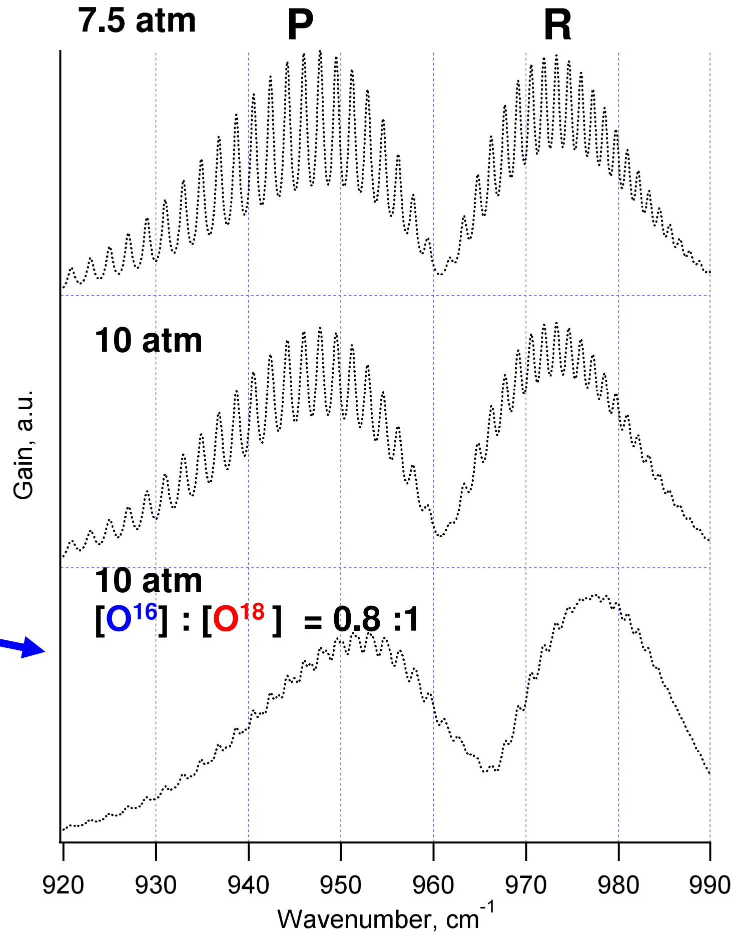
1) R-branch *vs.* P-branch: smaller line spacing (1.3 cm^{-1} and 1.8 cm^{-1} respectively)

2) Increased pressure: pressure broadening

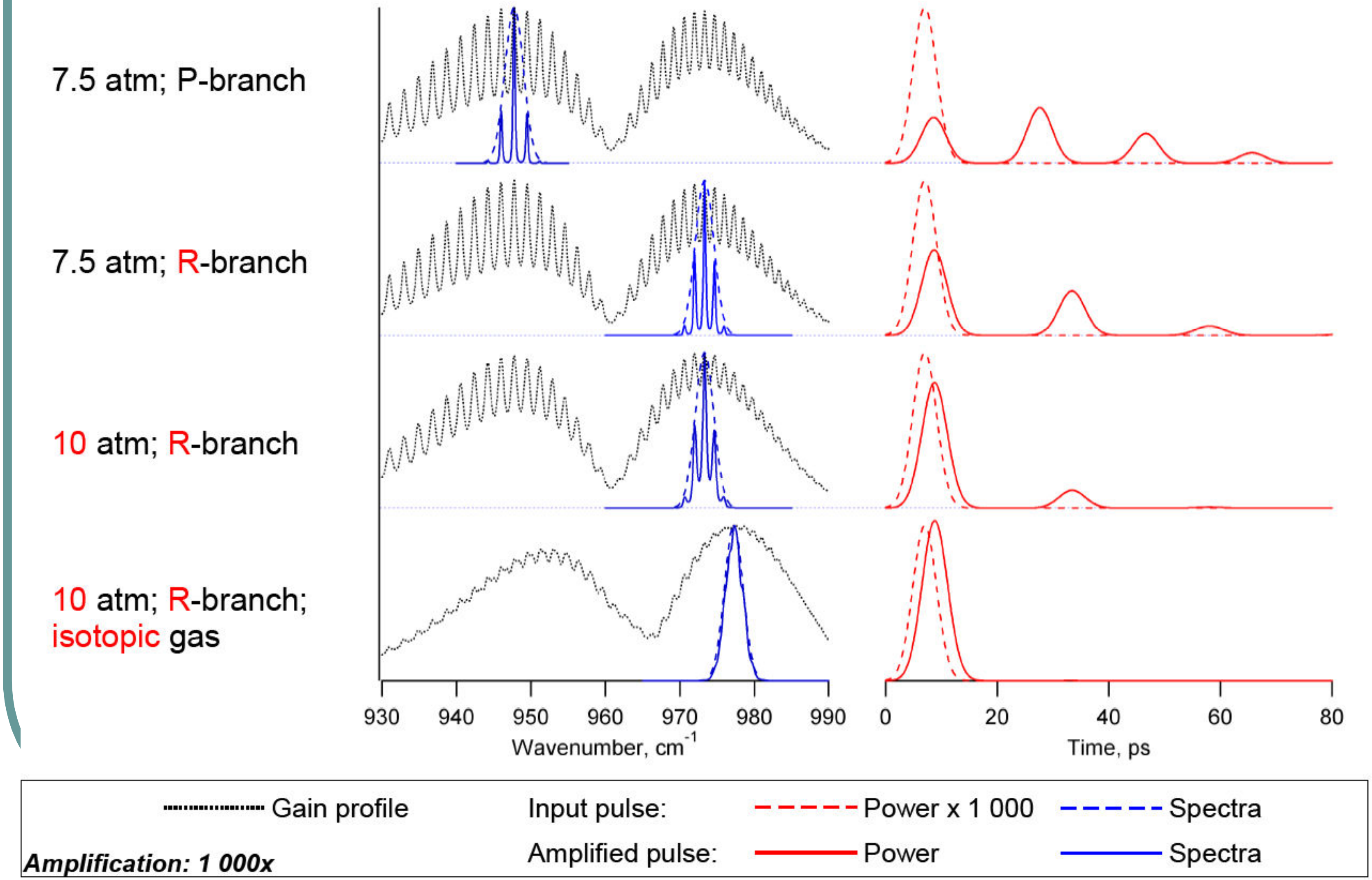
3) Isotopic mixture: higher effective line density

=> Smoother gain spectrum



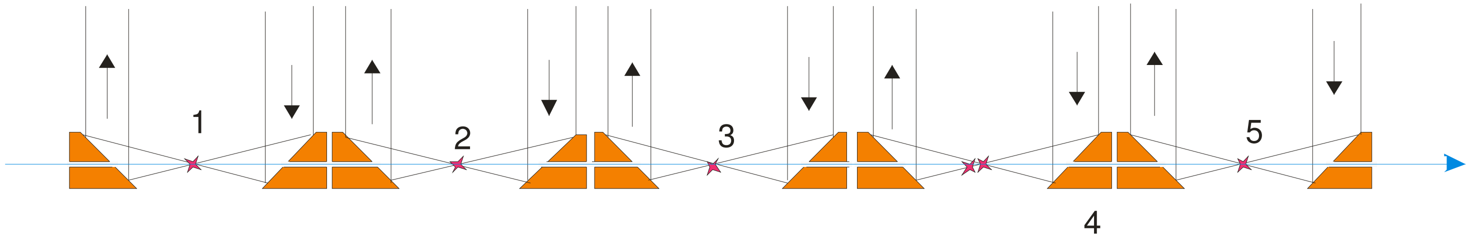


From trains to a single pulse

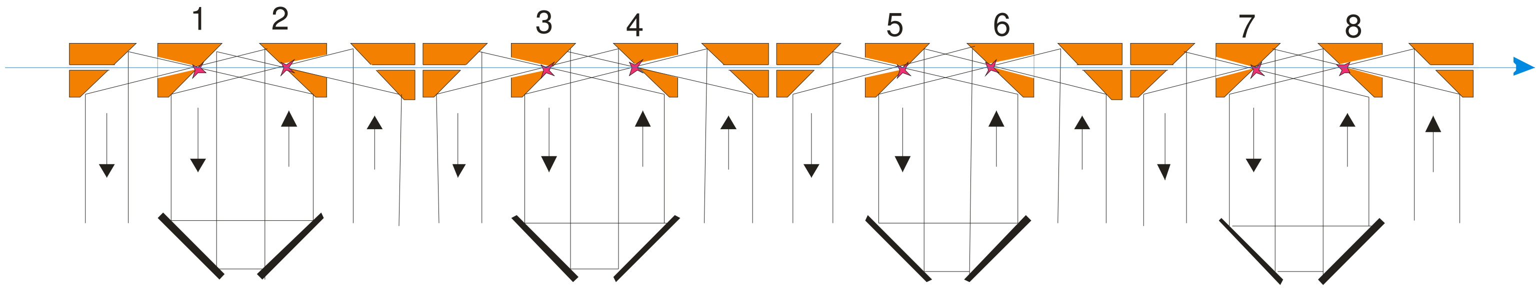


Assembling multiple interaction points

Standard configuration: 5 IPs

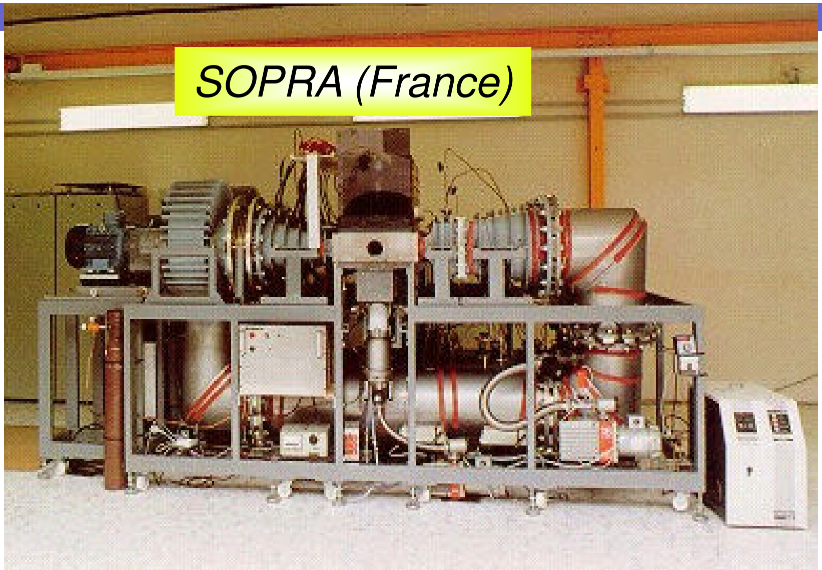


Compact configuration: 8 IPs, shown with 4 lasers



Travel distance between two coupled IPs for the laser pulse is adjusted to interact with two consecutive electron bunches.

Commercially available lasers



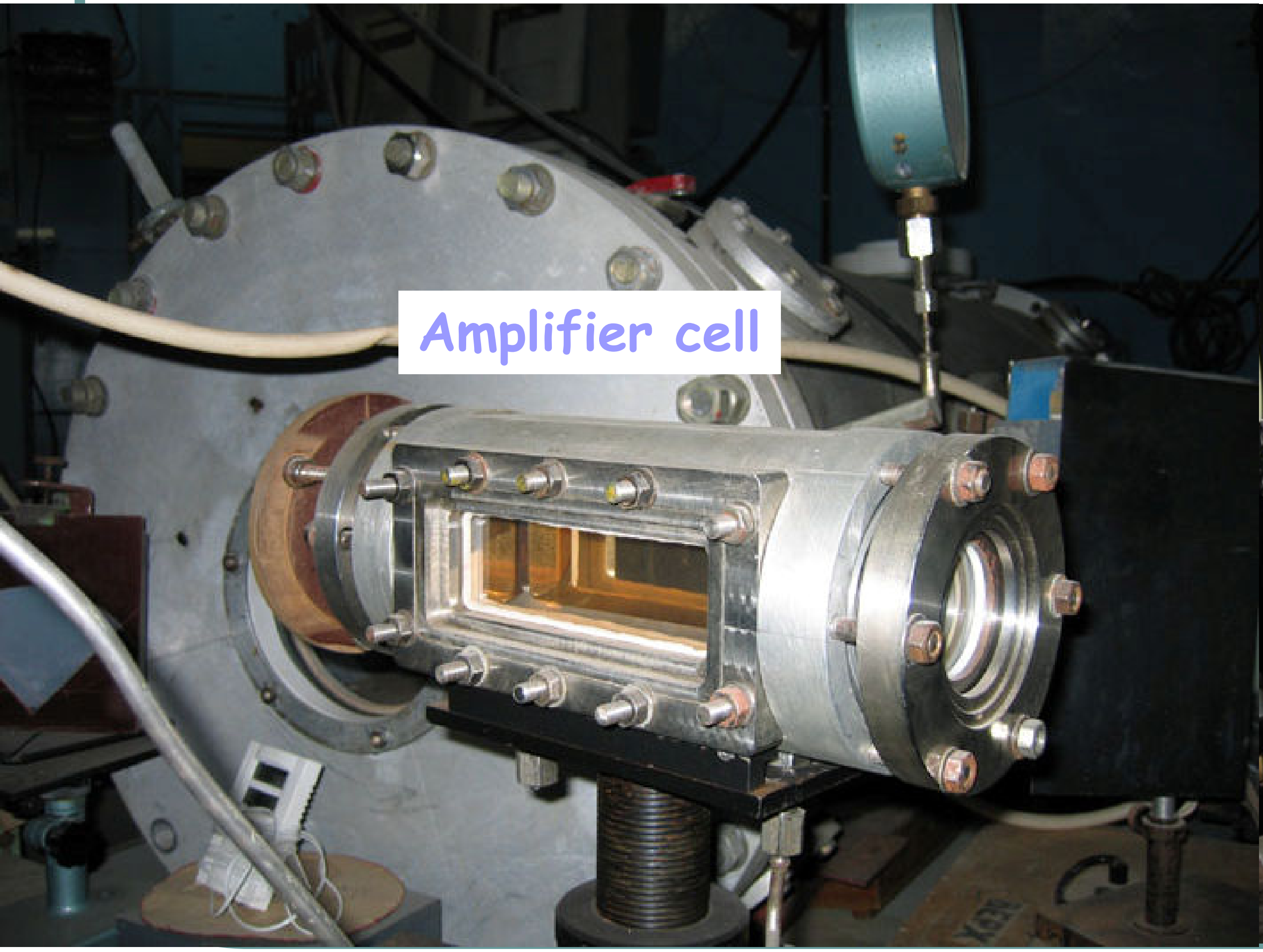
SOPRA (France)

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

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

SDI (South Africa)

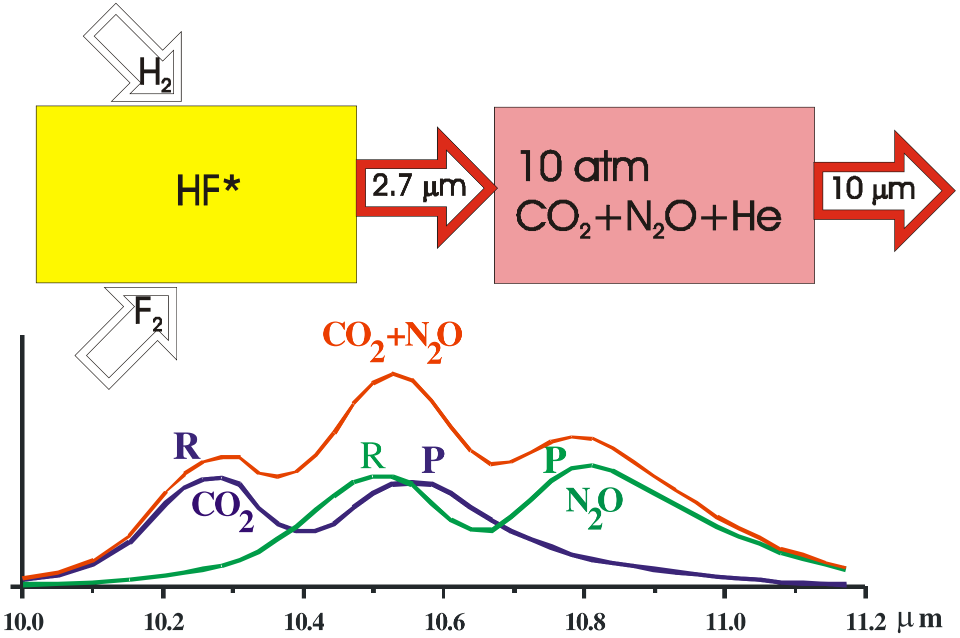
High-pressure CO_2 laser amplifier with optical pumping



Courtesy of M. Azarov

Russian Academy of Science

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



H_2

HF*

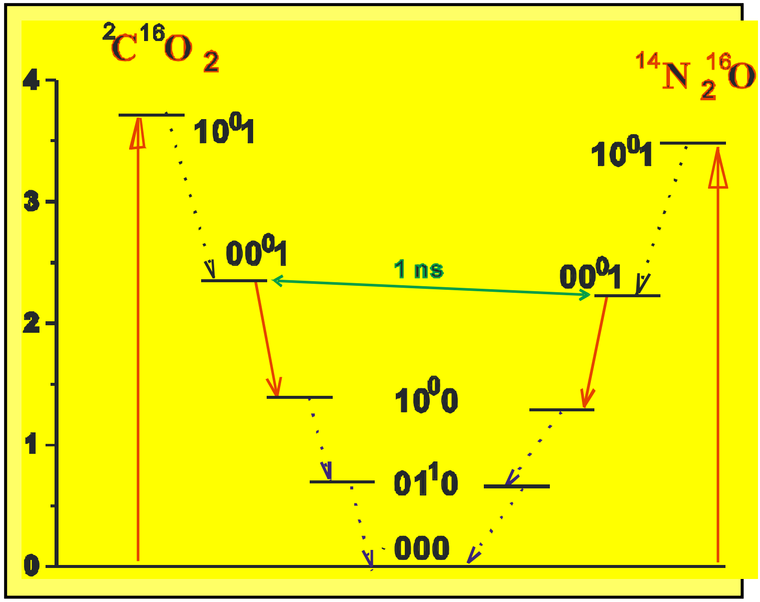
2.7 µm

10 atm

CO_2+N_2O+He

10 µm

F_2



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

Add multile pumps to expand time interval

Courtesy of M. Azarov

Russian Academy of Science

Some essentials of Compton LINAC approach

1. Linac versus Cyclotron

- Horiz. emittance in cyclotron - difficulty for the *e*-beam focusing. This reduces the laser/*e*-beams' overlap, the efficiency of γ production, and results in extra divergence of the γ-beam. In addition, it requires a bigger hole in the mirrors, so causing extra losses from the laser beam.

Some essentials of Compton LINAC approach

2. Laser cavity versus interferometric cavity

- A high-finesse cavity for enhancing the SSL's field rules out using relatively lossy mirrors with a hole. As a result, there would be a several degree tilt between the axes of the *e*-beam and laser beam that would reduce the efficiency of their interaction compared with a pure backscattering geometry.

Some essentials of Compton LINAC approach

3. λ=10 μm versus λ=1 μm

- Needs 10 times less energy for the same photon number.
- Needs 3 times longer linac, but:
  - a 1.6 GeV e-beam has a 3 times bigger angular divergence than a 4.75 GeV beam. This comes on top of the 3 times bigger 1/γ divergence of a gamma beam.
  - This conflicts with the approach of multiple bacscattering IPs (mirrors with holes)

Conclusions

- We proposed a self-consistent approach to PPS based on combination of linac with a CO_2 laser
- This approach is supported by prior demonstrations of the Compton x-ray yield, experiments and simulations of the pulse train circulation in the laser cavity that includes a Compton IP.
- Isotopic CO_2 gas will be tested soon.
- Available commercial lasers will support a high-repetition-rate regime.
- Demonstration of laser pulse trains closer to the PPS requirements (energy per pulse, uniformity) requires extensive reconfiguring of the BNL laser system.