Present status of ATF LASERS
(CO_2 & YAG)

Marcus Babzien

ATF laser personnel

Igor Pogorelsky	CO_2 "owner"/operator
Igor Pavlishin	operator, discharge technology
Marcus Babzien	YAG "owner"/operator
Daniil Stoliarov	short-pulse upgrades
Karl Kusche	laser safety, computer controls, data communication
Donald Davis	mechanical support
Mikhail Poliansky	LDRD post-doc, new arrival

+ ATF designers, technicians, electronic engineer, computer engineer

OUTLINE:

Introduction

Principles

What is new since User's Meeting 2005

YAG status – aging gracefully

5-ps 1-TW CO_2 regime

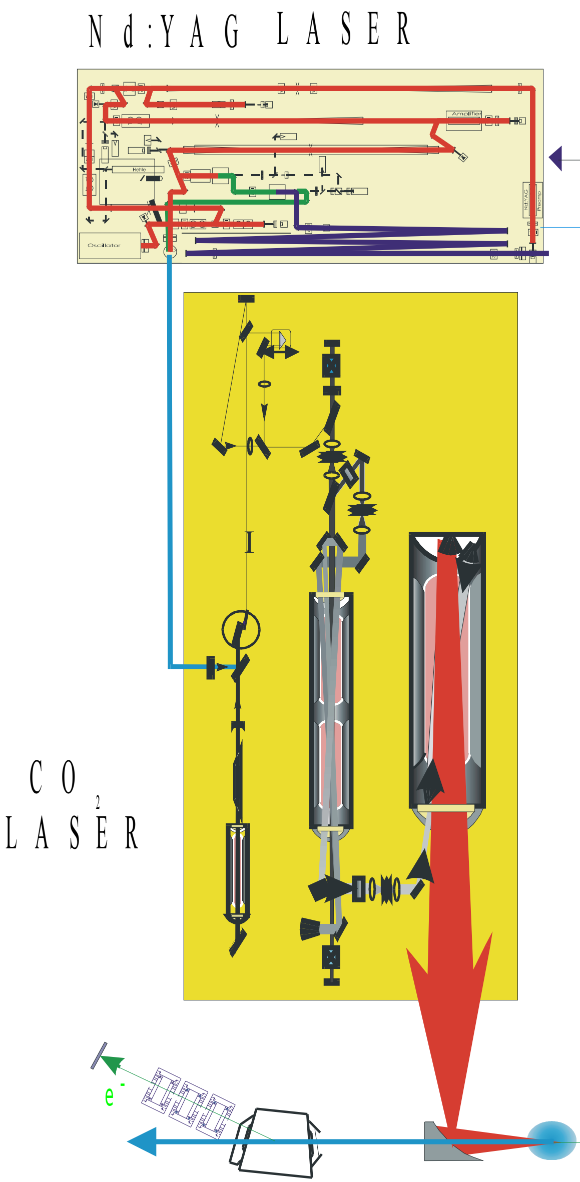
- Laser front end
- Pulse measurements
- User's experiments

CO_2 configuration for micro-bunch experiments

- PASER, Resonance PWA

Intra-cavity pulse train

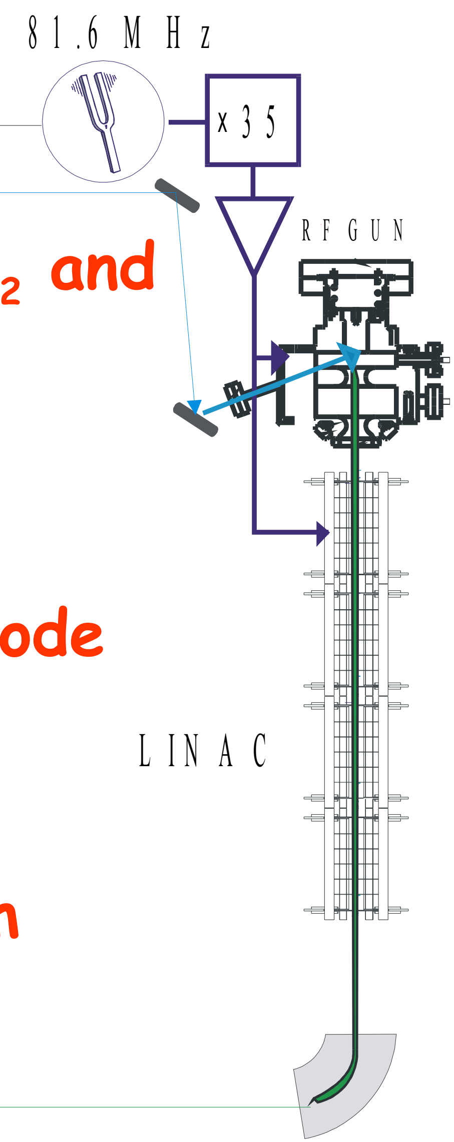
- ILC LDRD



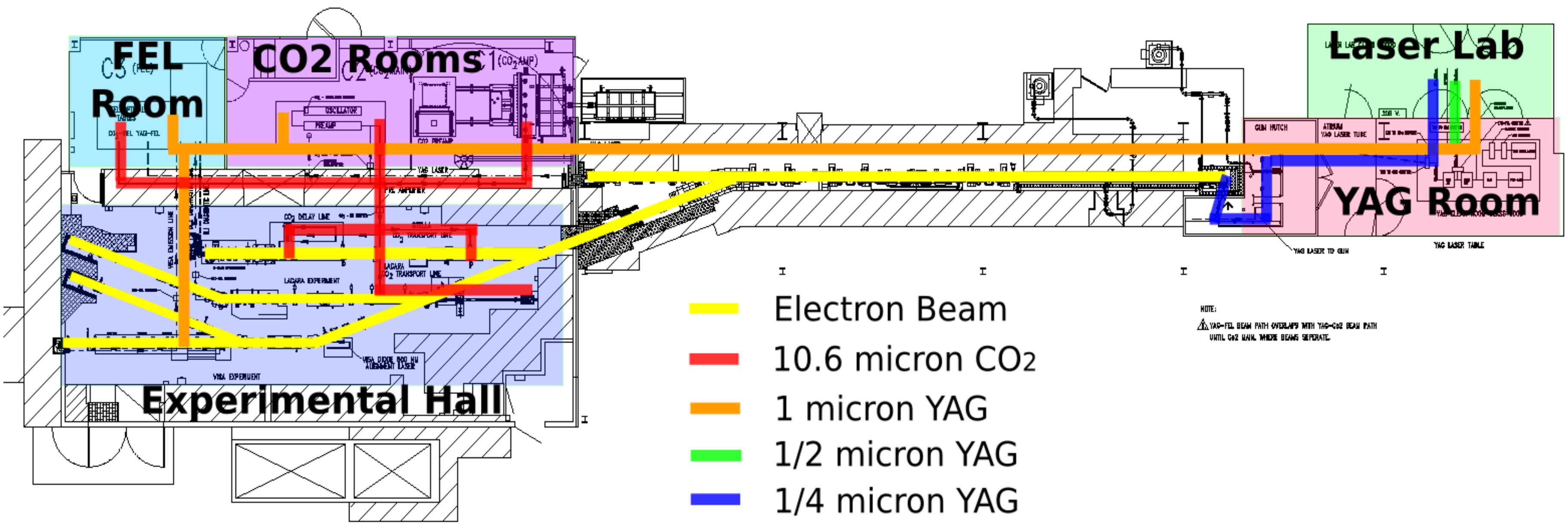
Synchronized to linac, CO_2 and YAG Lasers are principal components of the ATF

YAG: drives RF photocathode
slices ps CO_2 pulse

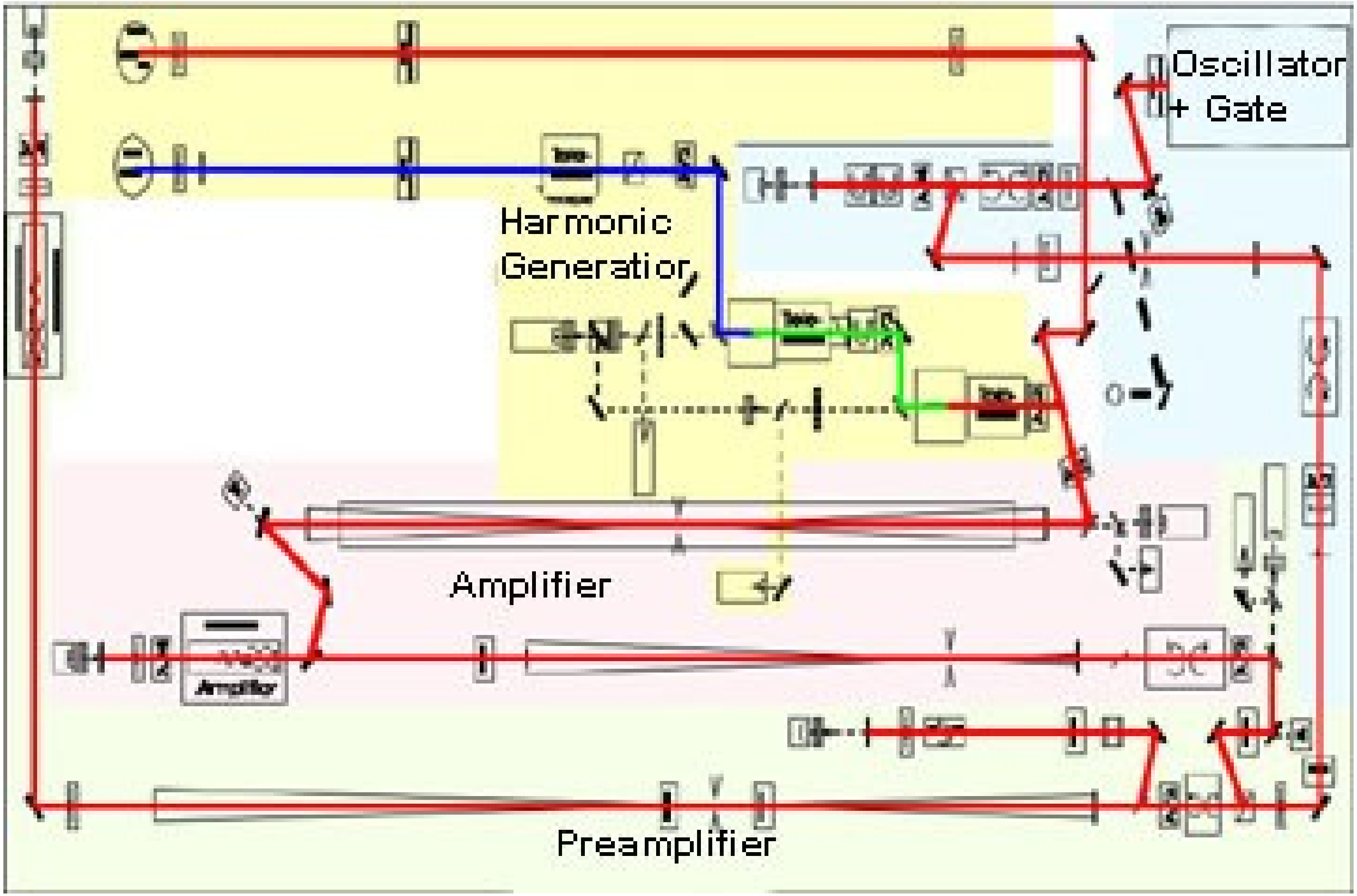
CO_2: used in laser/e-beam and laser/matter interaction experiments

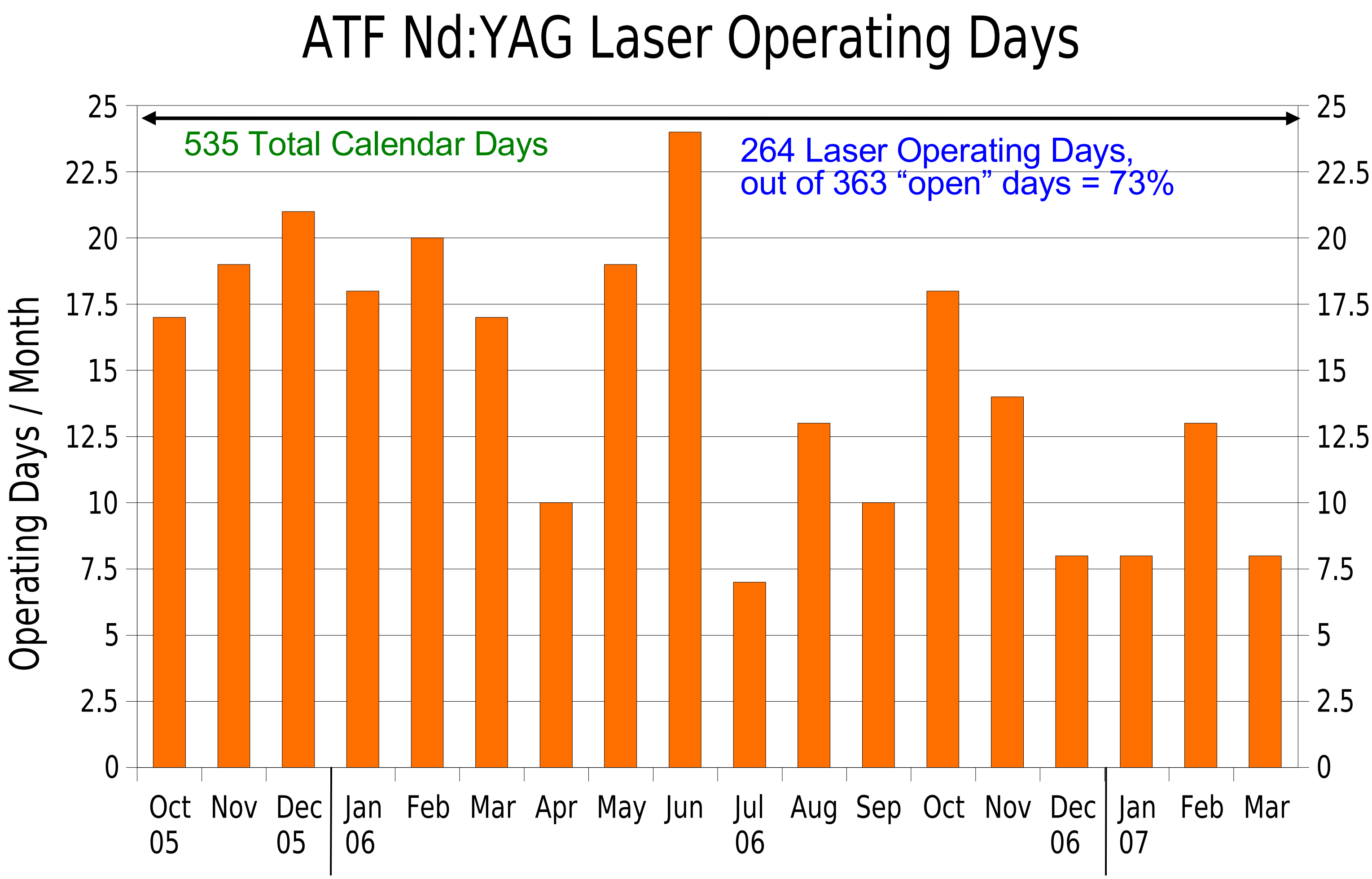


Facility Layout



ATF Nd: YAG Laser - Functional Units and Beam path




ATF Nd:YAG Laser Operating Days
535 Total Calendar Days
264 Laser Operating Days,
out of 363 “open” days = 73%
Operating Days / Month
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Oct 05
Nov
Dec 05
Jan 06
Feb
Mar
Apr
May
Jun
Jul 06
Aug
Sep
Oct
Nov
Dec 06
Jan 07
Feb
Mar

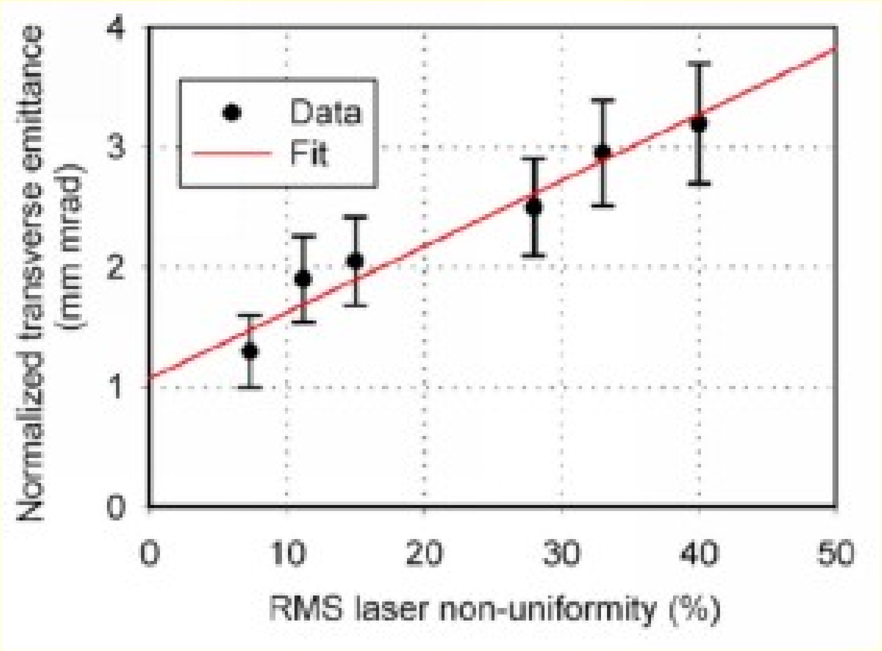
YAG Status - Demonstrated Performance

Demonstrated Nd:YAG System performance:	
Energy on cathode	0-40 μJ
Pulse duration (FWHM):	8 ps gaussian
Range of beam size on cathode (Ø)	0.2 - 3 mm
Top-Hat Beam Profile Modulation (P-P)	<20%
Shot-to-shot stability (rms):	
Timing	<0.2 ps
Energy	<2 %
Pointing (fraction of beam Ø)	<0.3%
Drift (8 hour P-P)	
Timing	<1ps
Energy	<15 %
Pointing (fraction of beam Ø)	<1%

YAG Upgrades – Beam Profile

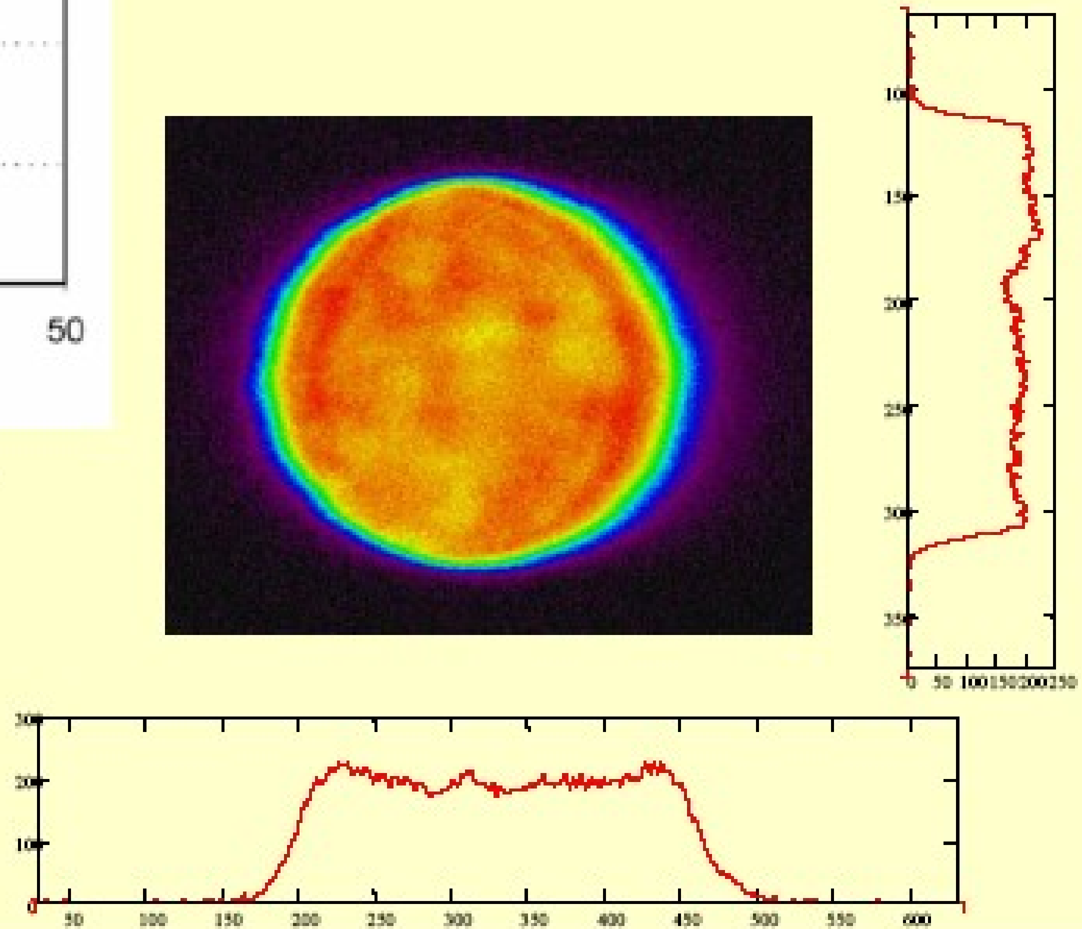
Uniformity of electron emission from photocathode affects emittance.

Laser uniformity is limited by phase errors in optical elements that are transferred to the intensity domain as the beam propagates to the photocathode.

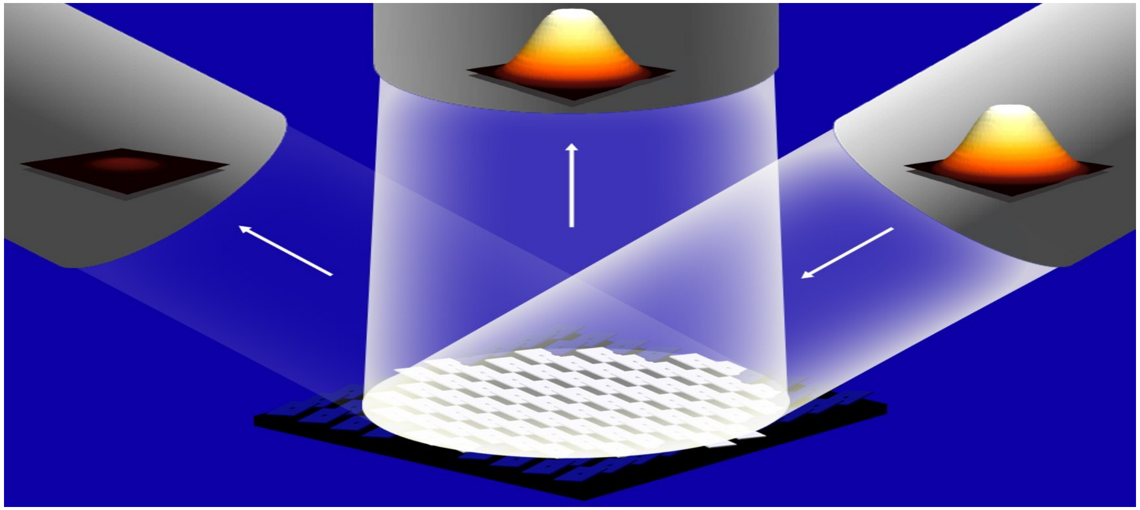


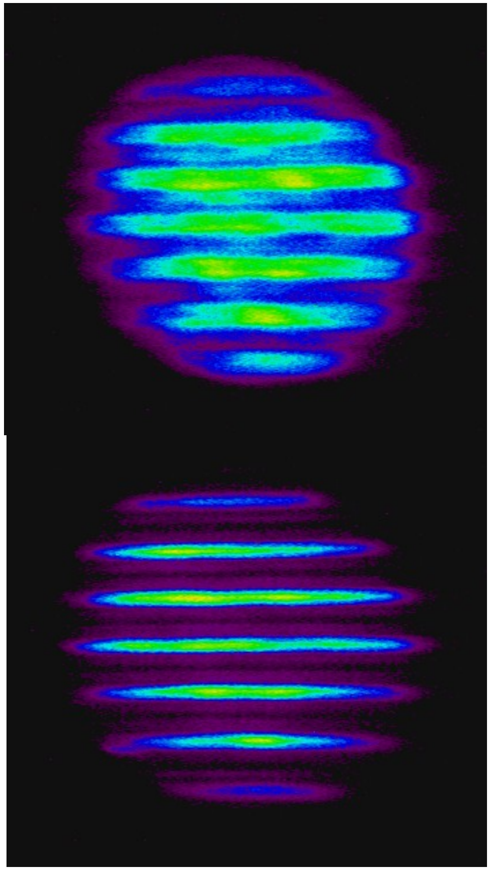
Some elements such as non-linear crystals and Pockels cells are not easily fabricated to such tight tolerances (<λ/20).

Therefore it is very challenging to passively improve the uniformity of the beam.



YAG Upgrade - Active Profile Shaping





A micromirror array as used in commercial projectors is robust enough to serve as an active beam shaper for a laser beam.

Mirrors are 13 micron square in a 1024 x 768 matrix.

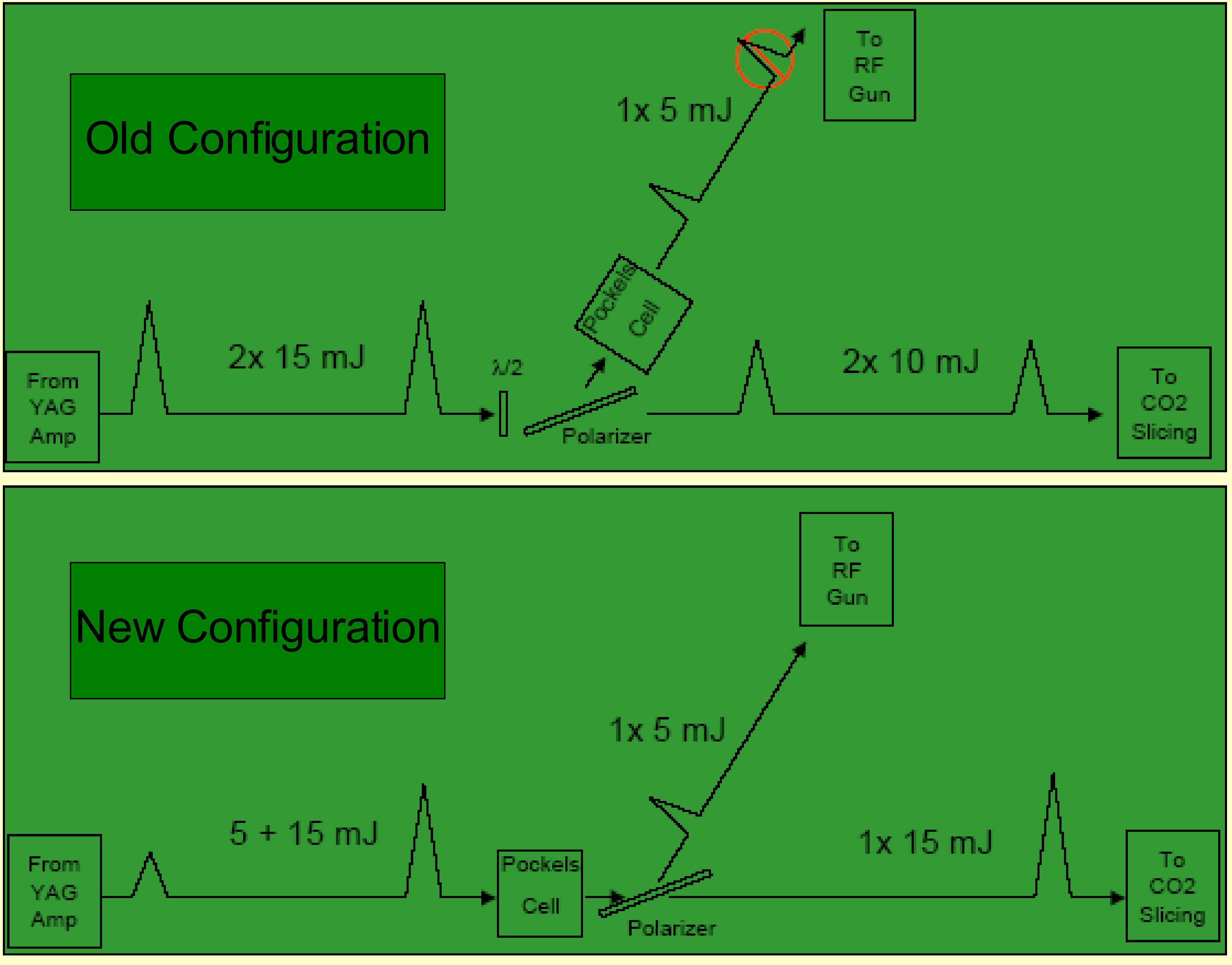
Individually addressable into one of two tilt positions.

Array is effectively a grating with electronically variable-blaze.

Size of one mirror is below the resolution limit of the transport optics, so groups of mirrors together allow fine control of intensity at every point in beam.

Unlike deformable mirrors, works well for low-brightness “tophat” distribution, and incapable of damaging photocathode with tight focus.

Already tested with client/server software to characterize beam emittance versus laser modulation.


Old Configuration
From YAG Amp
2x 15 mJ
λ/2
Polarizer
Pockels Cell
1x 5 mJ
To RF Gun
2x 10 mJ
To CO2 Slicing
New Configuration
From YAG Amp
5 + 15 mJ
Pockels Cell
Polarizer
1x 5 mJ
To RF Gun
1x 15 mJ
To CO2 Slicing

YAG System Replacement: Building an Advanced Drive Laser

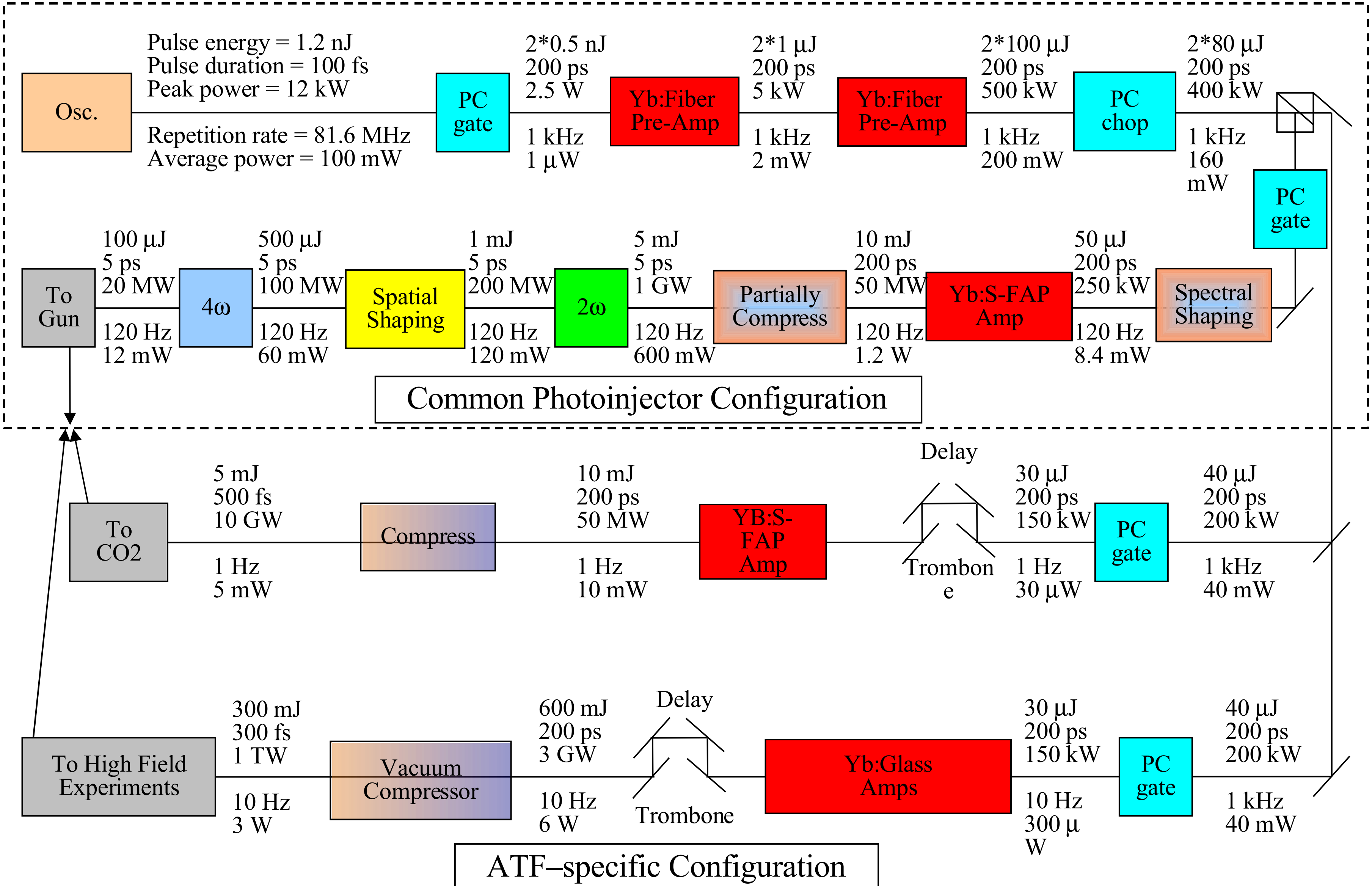
The ATF Nd:YAG system has demonstrated excellent performance and is aging well, yet some subsystems are over 20 years old; a replacement is now overdue and we have started development of a purpose-built next generation drive laser.

Better performance than standard off-the-shelf Ti:Sapphire or other laser systems will be achieved by:

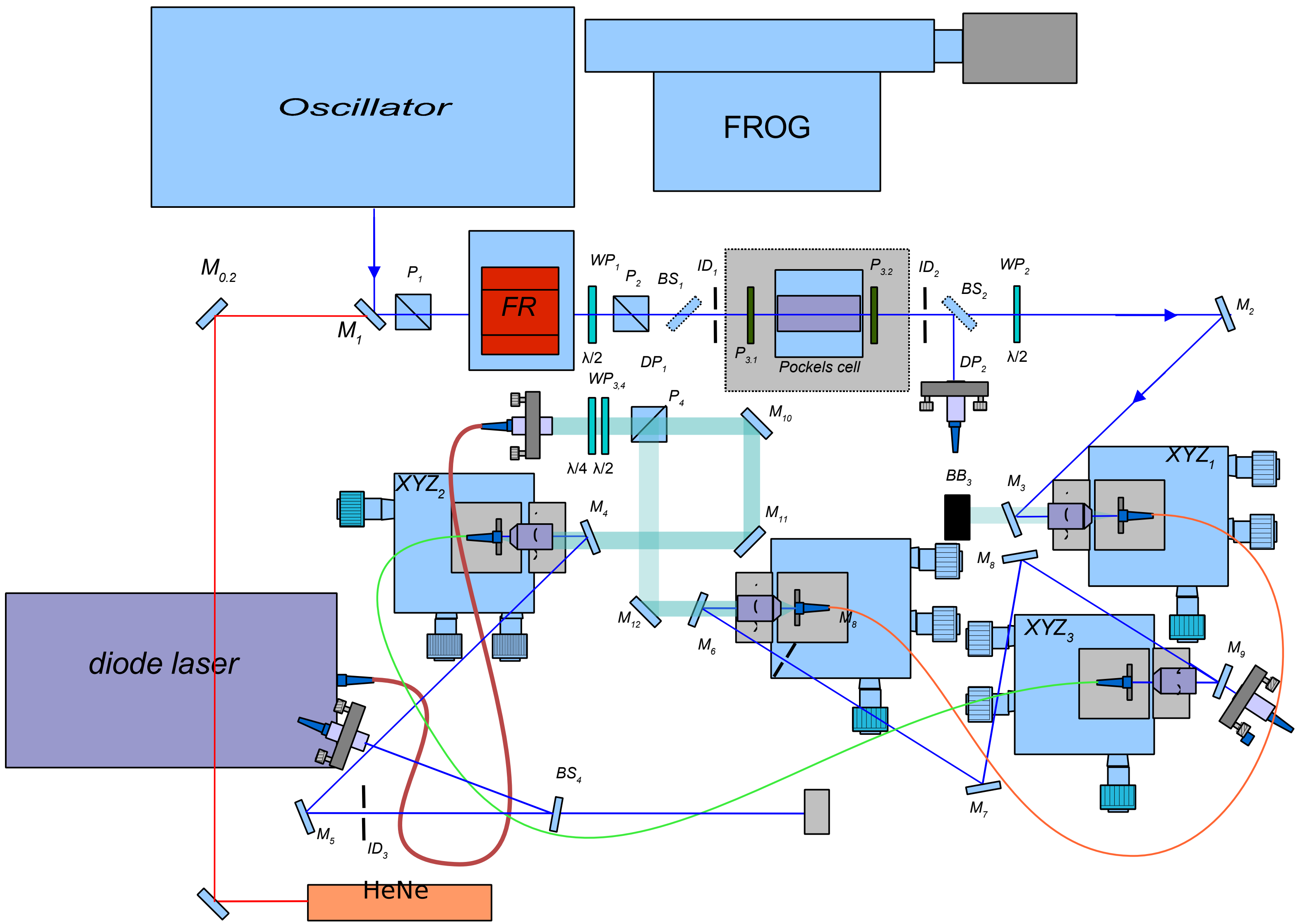
- Relying exclusively on directly diode-pumped systems instead of more complex, large and failure prone lasers
- Choose efficient 1 μm lasing hosts in a mixed gain media configuration to minimize thermal issues and reduce system size
- Integrate high-level commercial components in-house to minimize development time while maintaining local expertise
- Continue to provide optical synchronization of facility by seeding additional amplifiers for CO_2 laser slicing & NIR TW laser
- We expect to achieve the following improvements to return ATF to the forefront of photoinjector drive laser performance:

- 100 uJ available UV on cathode (3x more than now)
- Energy jitter 0.2% rms ~ 1% p-p (5x better than now)
- Timing jitter < 200 fs rms (already demonstrated)
- Profile Uniformity ≤ 5% p-p (from desired arbitrary profile) (3x better than now)
- Pointing Jitter ≤ 1% p-p (already demonstrated)
- Temporal shaping (currently limited to gaussian)
- Fast turn-on (already under 15 minutes)
- High Reliability (already provide >1500 hours / year)
- Simple operation (~turn-key) (almost there now!)

Advanced Drive Laser Block Diagram

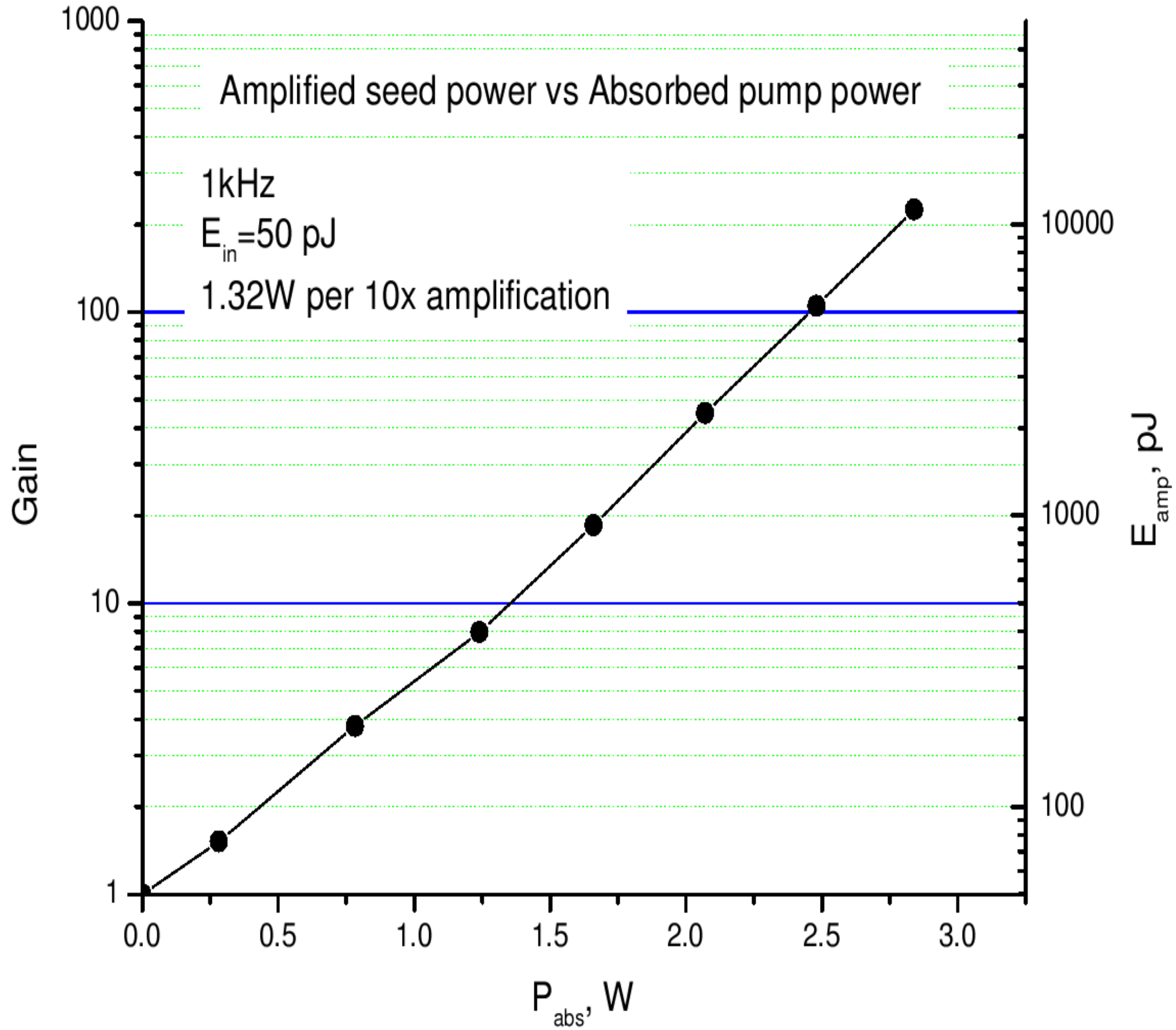


Advanced Drive Laser Test Stand Schematic



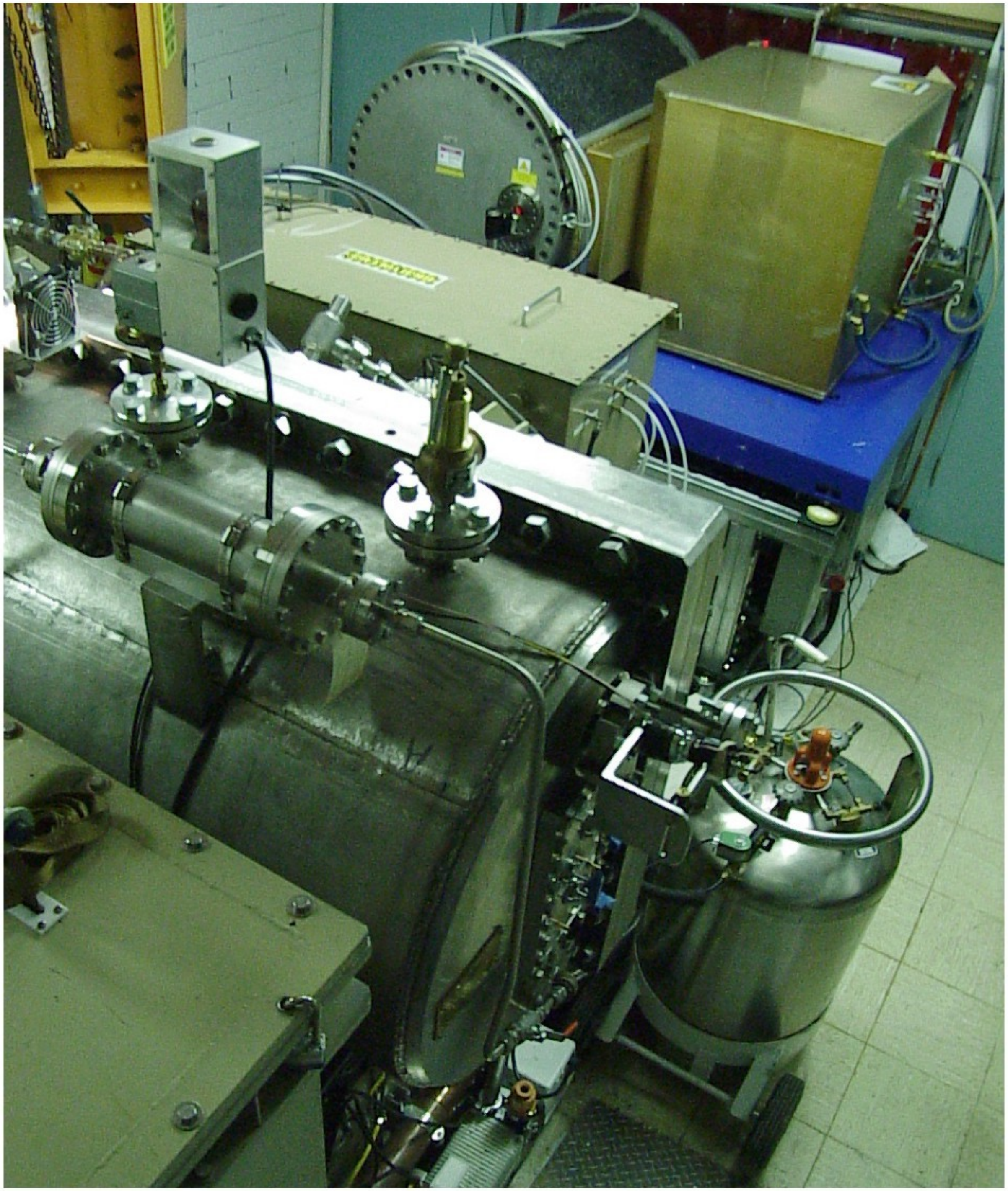
Advanced Drive Laser Progress

- Investigated gain of different first and second stage fiber amplifiers
- Operated at 1 kHz repetition rate
- Brought temporal diagnostic into operation and demonstrated short pulse amplification in first fiber stage
- Demonstrated gain →
- Achieved single pulse energy adequate to start CPOD experiment



Advanced Drive Laser Original Timeline

Year	Goals	Purchases	Cost (K$) ATF	Cost (K$) Users
1	Verify fiber preamp 1 performance up to ~ 1 uJ using ATF oscillator	fiber preamp 1 assembly with pump diodes		30
		short pulse diagnostic (FROG or GRENOUILLE)	18	
		miscellaneous optics and diagnostics	20	
	Prepare oscillator & preamp 1 for optical particle detector experiment			
2	Test fiber preamp 2	multimode fiber	3	
		pump diodes	25	
		misc optics	10	
	Assemble & test final amplifier using seed from preamp chain	Yb:S-FAP amplifier crystal	10	
		pump diodes	15	
		Pockels cells	20	
		misc optics	20	
3	Construction of final gun driver	new beam transport to gun hutch	15	
		temporal shaper	40	
		misc optics	20	
			216	30



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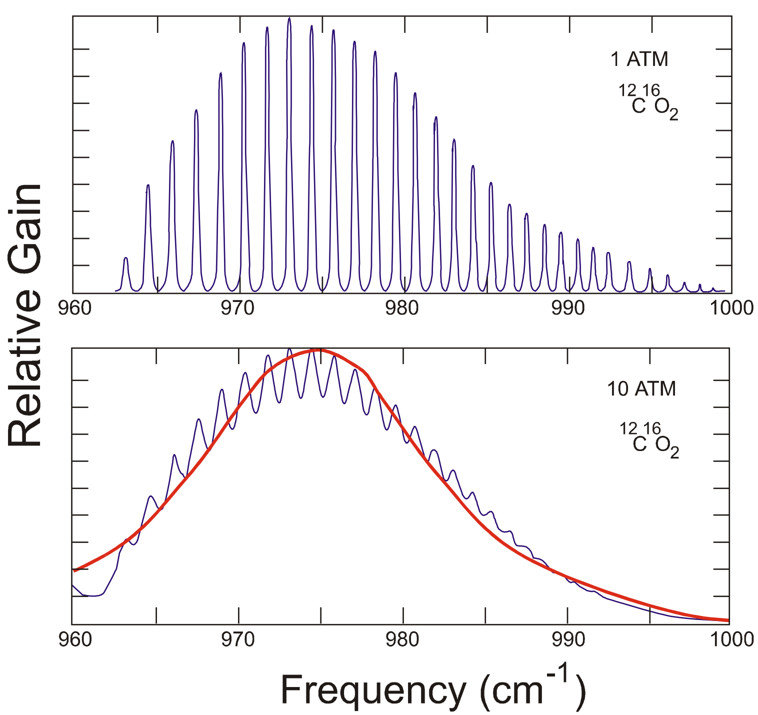
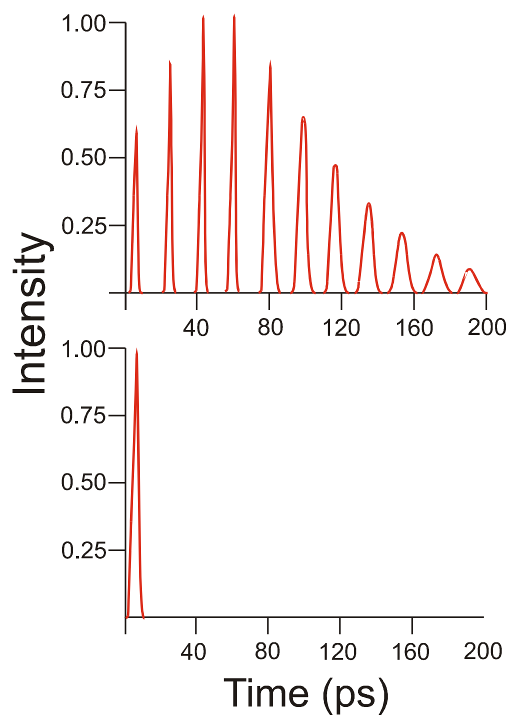
Bandwidth limited amplification of ps CO_2 laser pulses

Gain Spectrum



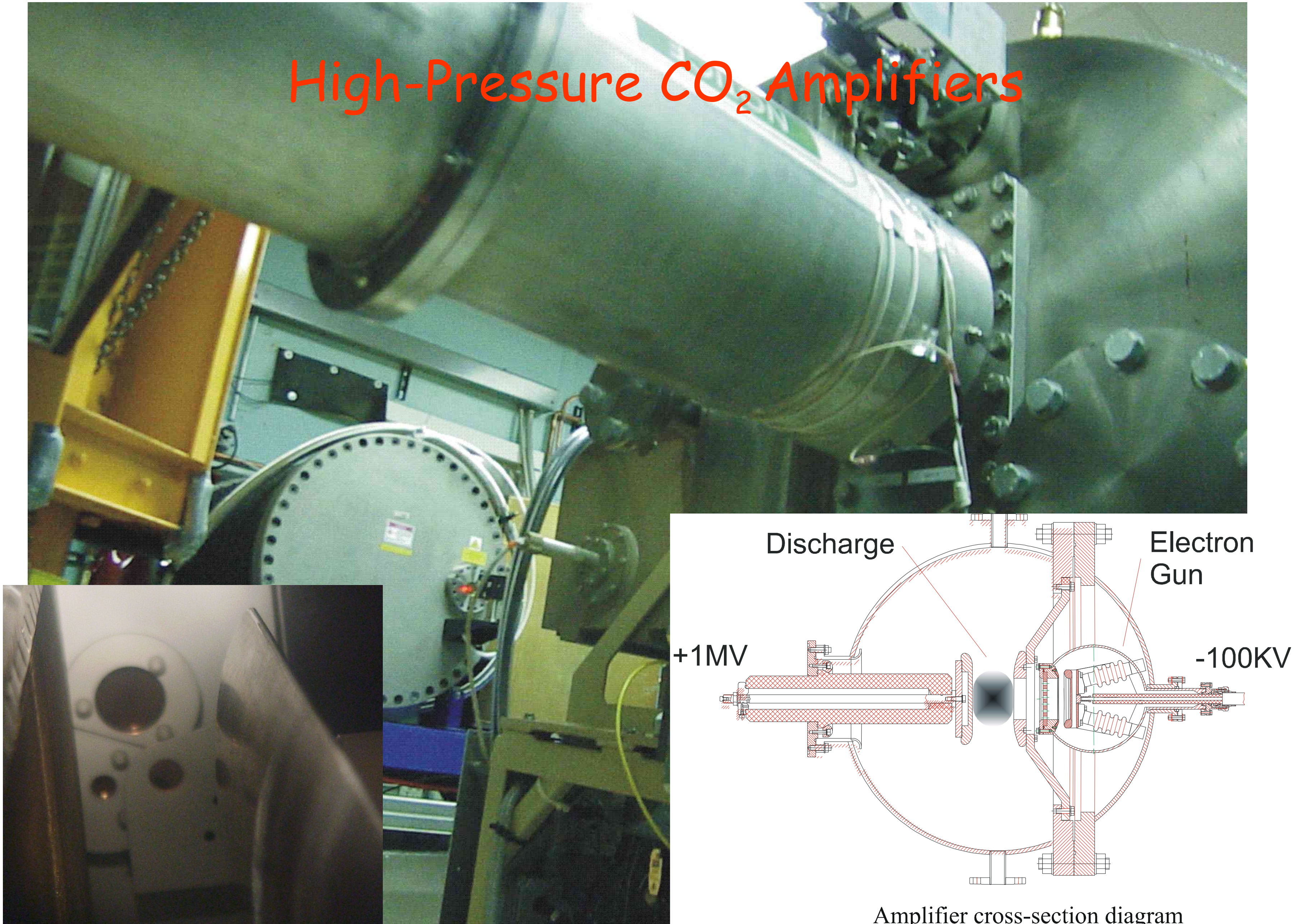
Amplified Picosecond Pulse



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

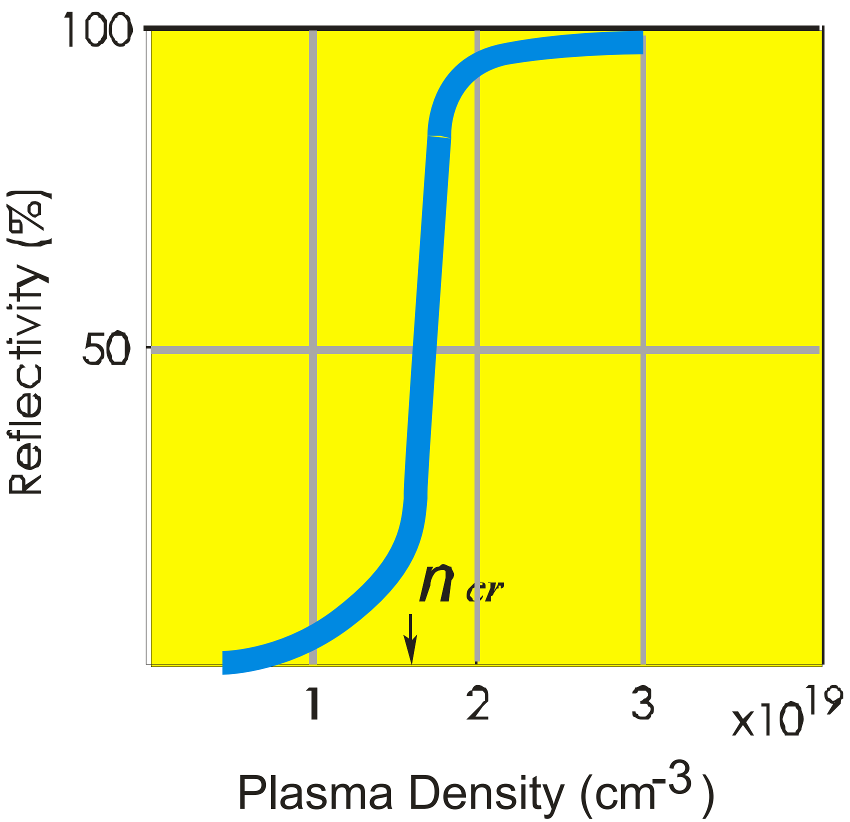
At 10 atmospheres, collisional broadening produces overlap of the rotational lines into the 1 THz wide quasi-continuous gain spectrum, and pulses as short as 1 ps can be amplified without distortion.

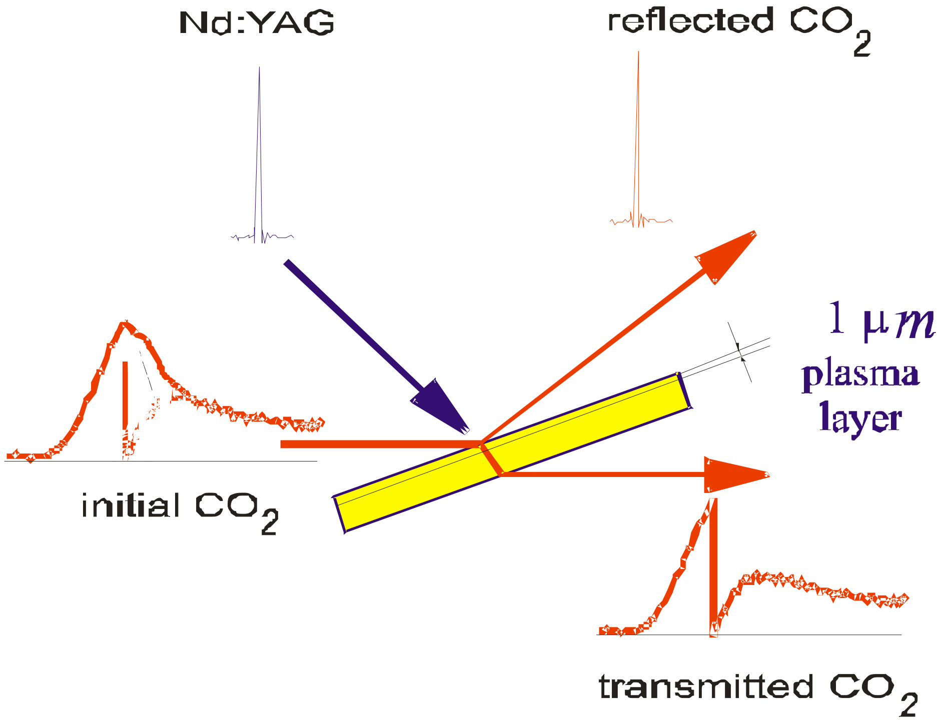
High-Pressure CO_2 Amplifiers



Amplifier cross-section diagram

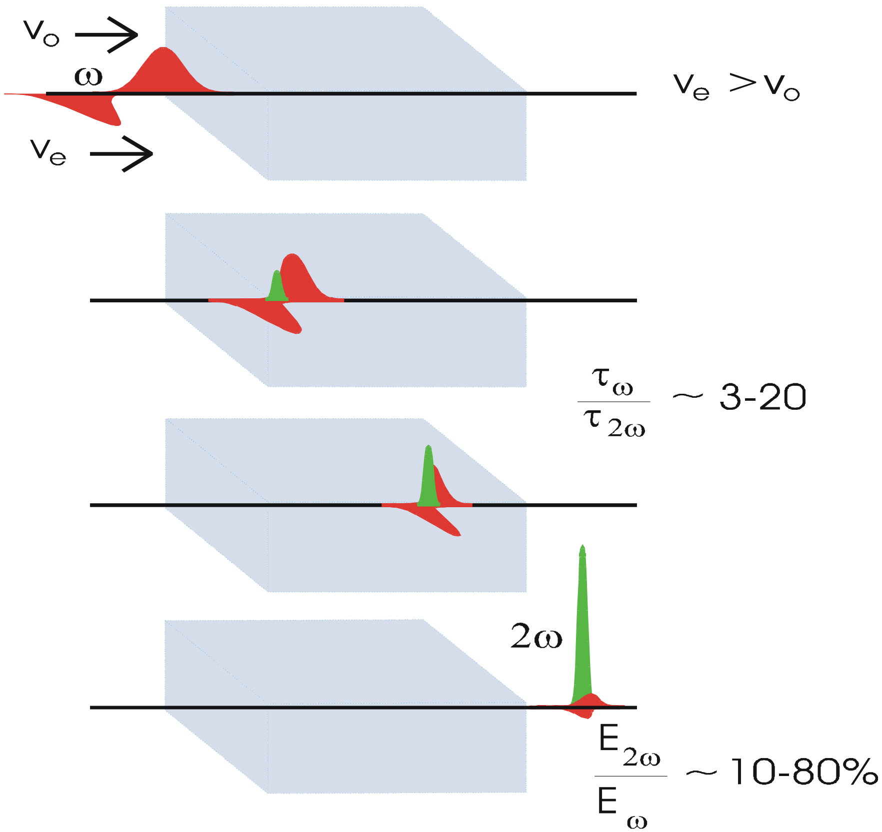
Principle of Semiconductor Optical Switching





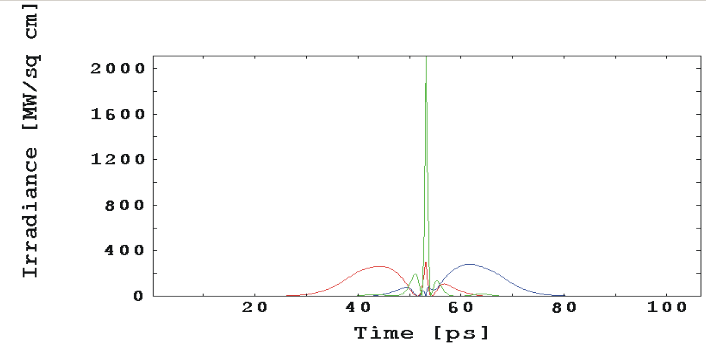
SH compression in KD*P crystal

Starting with the existing long pulses (14 ps) from the ATF YAG laser, second-harmonic compression* can be used to generate ps to sub-ps green pulses.



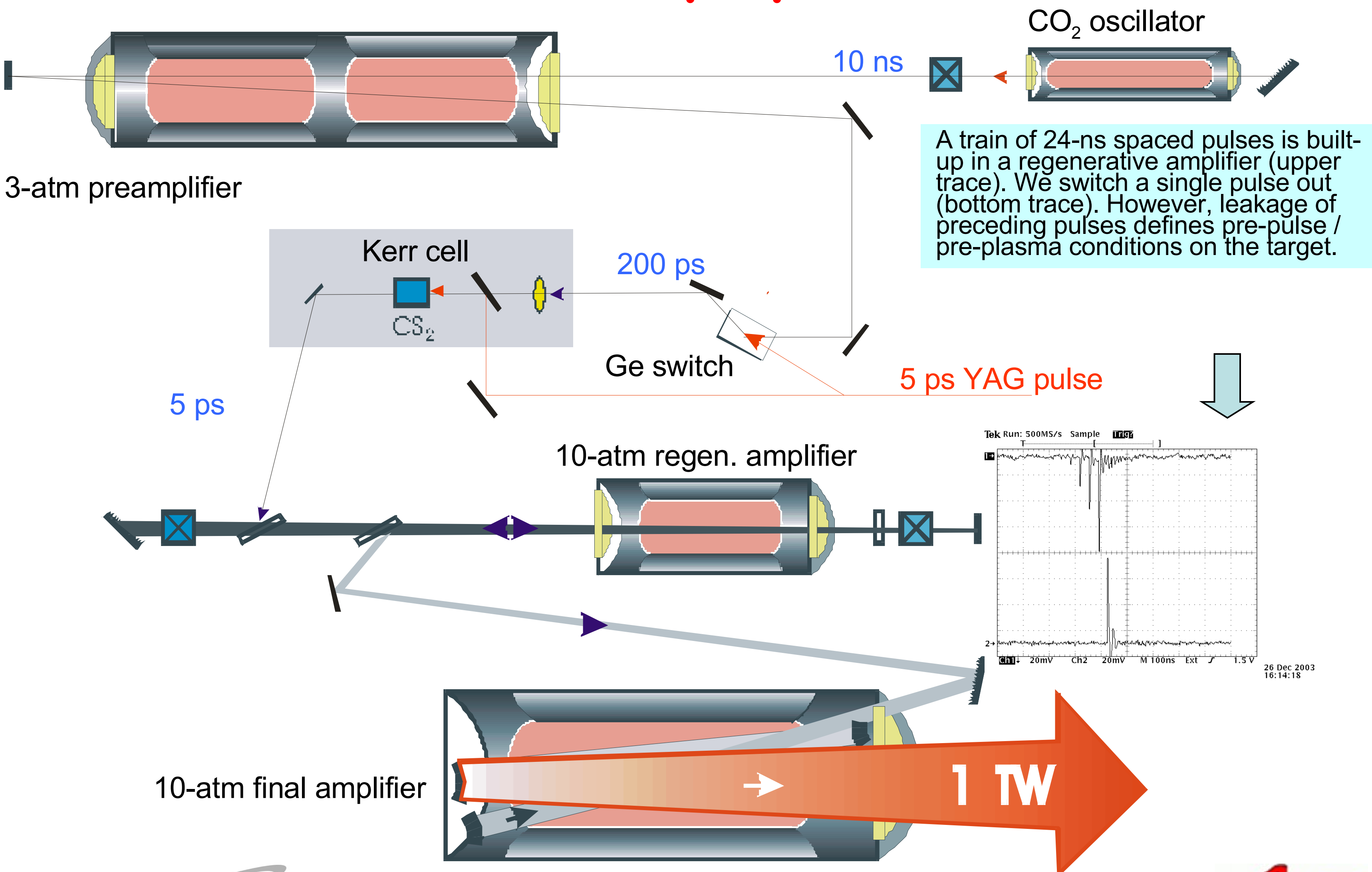
*Y. Wang, and R. Dragila, Phys. Rev. A **41**, 5645 (1990)

SNLO code simulations of 1064 to 532 nm conversion in 10 cm crystal with group velocity mismatch.



- Measured compression from 1 micron to 532 nm with pulse duration decrease of 3-4x in a 10 cm KD*P doubler.
- Energy available at 532 nm is ~ 100 mJ, now limited by input energy.
- New Pockels cell is on order to more efficiently utilize 1 micron energy between gun and CO2 slicing.
- Multi-stage semiconductor slicing using both 1 micron & green pulses will allow few ps CO2 pulse generation for TW operation.

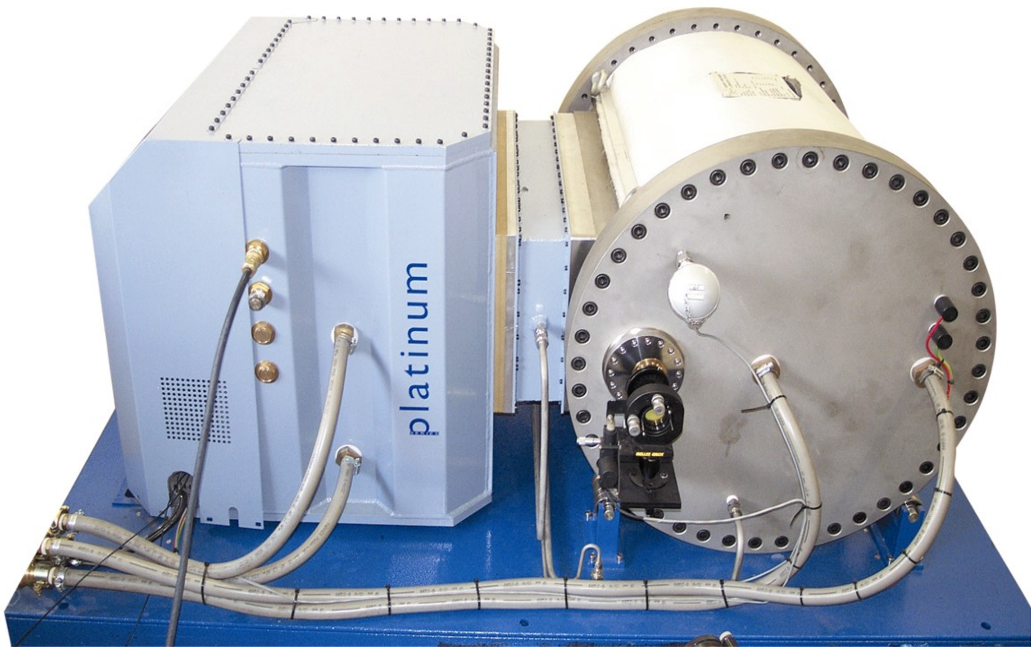
BNL/ATF CO_2 laser System delivers 1 TW, 5 ps pulses

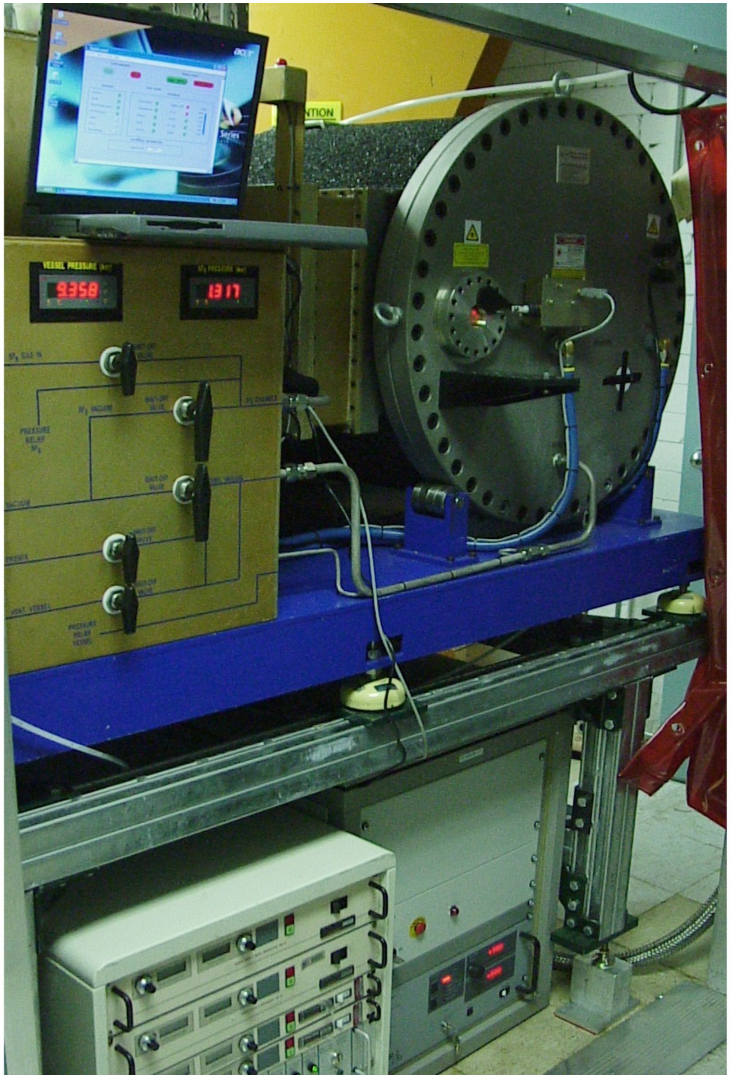


A train of 24-ns spaced pulses is built-up in a regenerative amplifier (upper trace). We switch a single pulse out (bottom trace). However, leakage of preceding pulses defines pre-pulse / pre-plasma conditions on the target.

Regenerative CO_2 laser amplifier

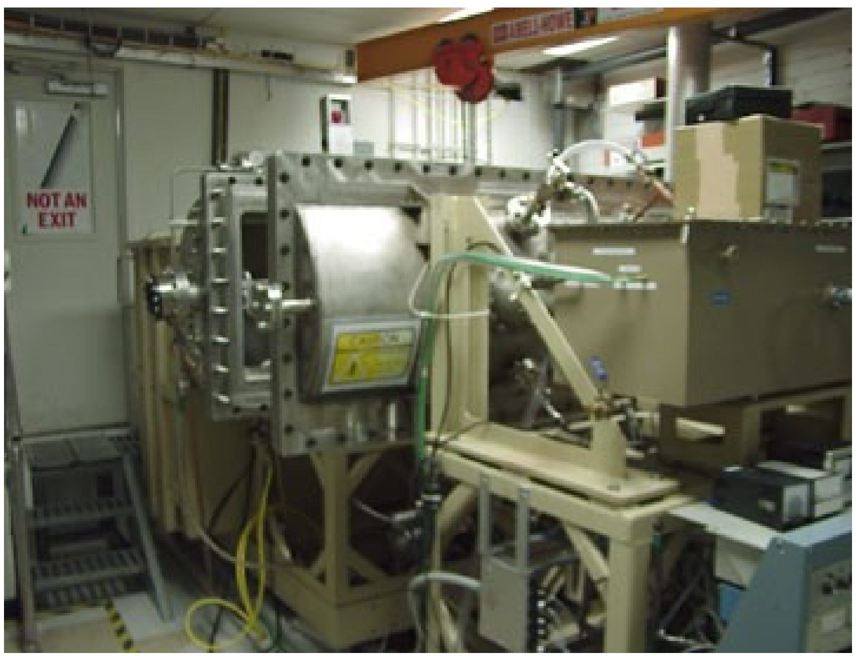
Pulse length	15-200 ps	3ps
Energy	30 mJ	
Repetition rate	5 Hz	
Peak power	2 GW	10 GW

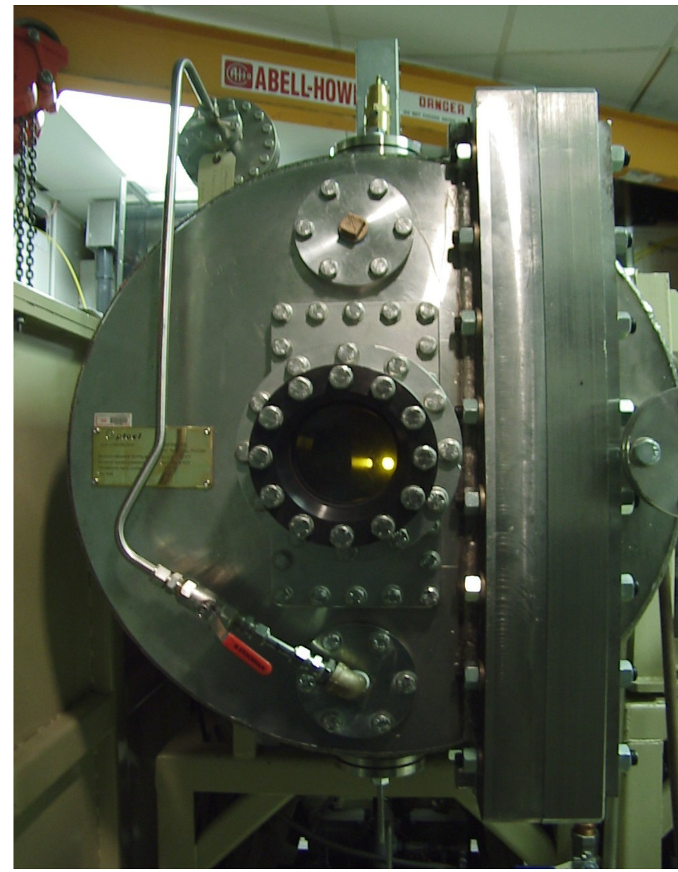




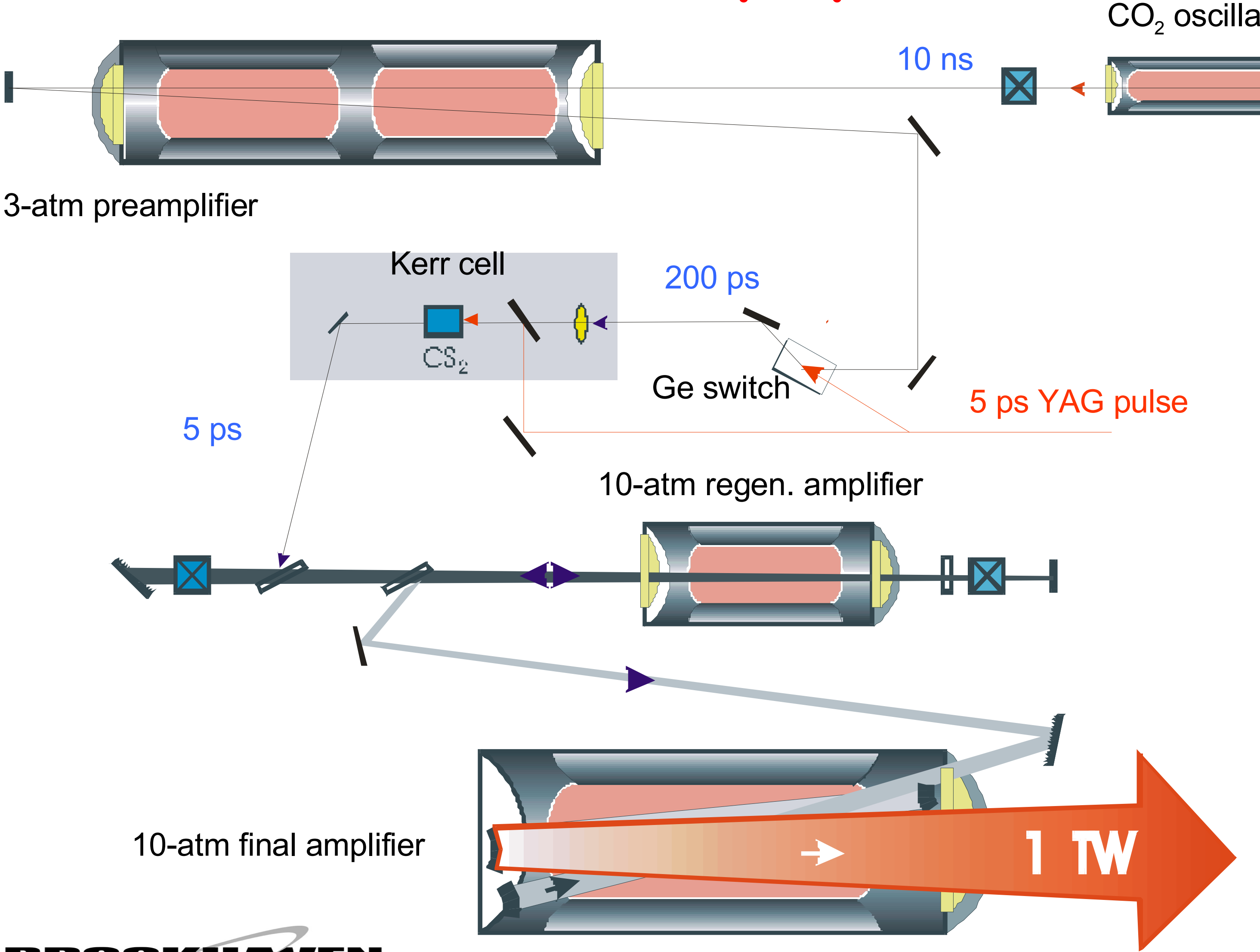
Demonstrated and potential CO_2 laser performance

Pulse length	5-200 ps	<1 ps
Energy	10 J	
Repetition rate	1 / 20 Hz (limited by power supply)	
Peak power	1 TW	>5 TW
Focal spot (σ)	30 μm	20 μm
Laser strength (*a*)	0.7	>2



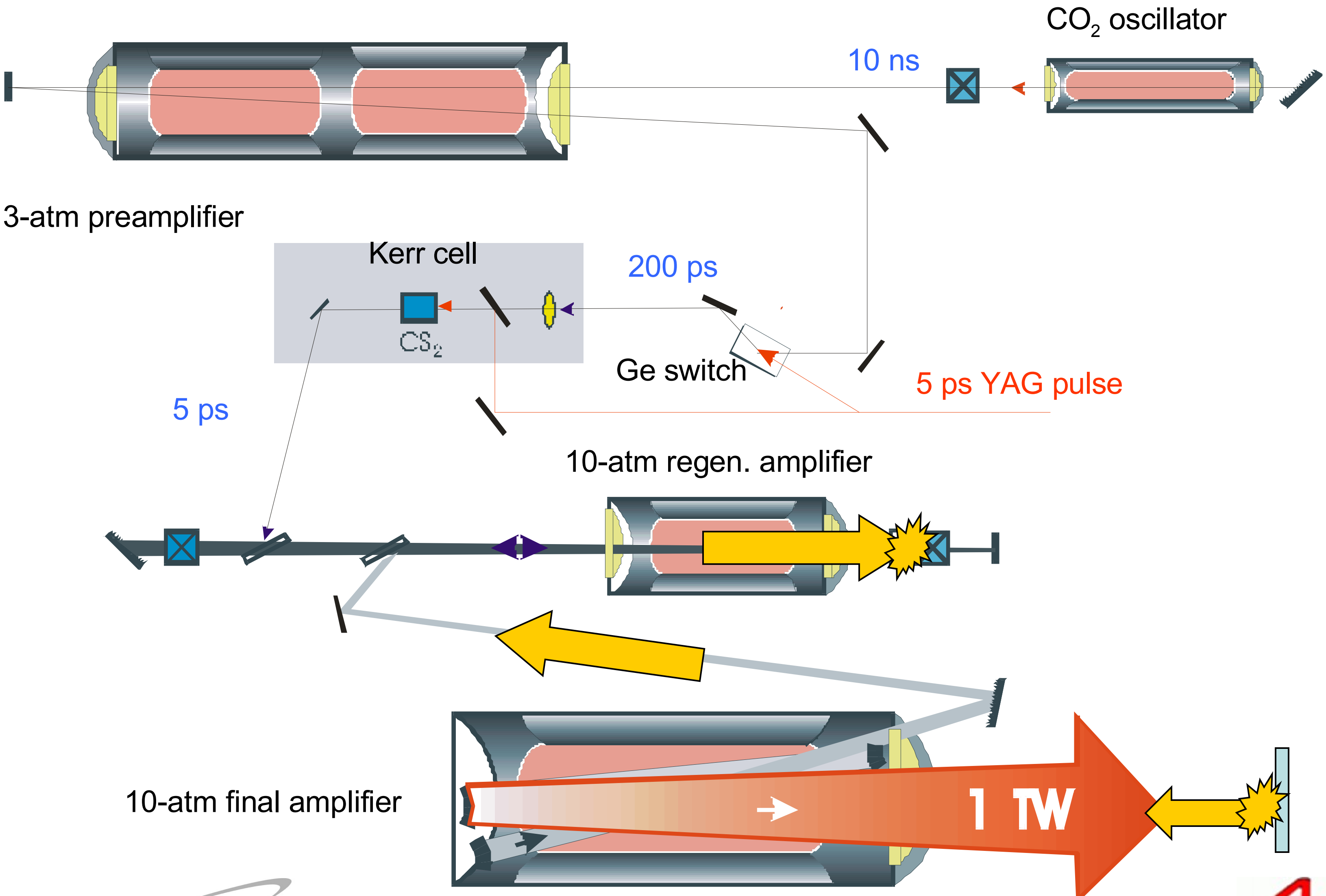


BNL/ATF CO_2 laser System delivers 1 TW, 5 ps pulses



The output beam is converted to circular polarized in order to protect the laser system from retro-reflection from the target.

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



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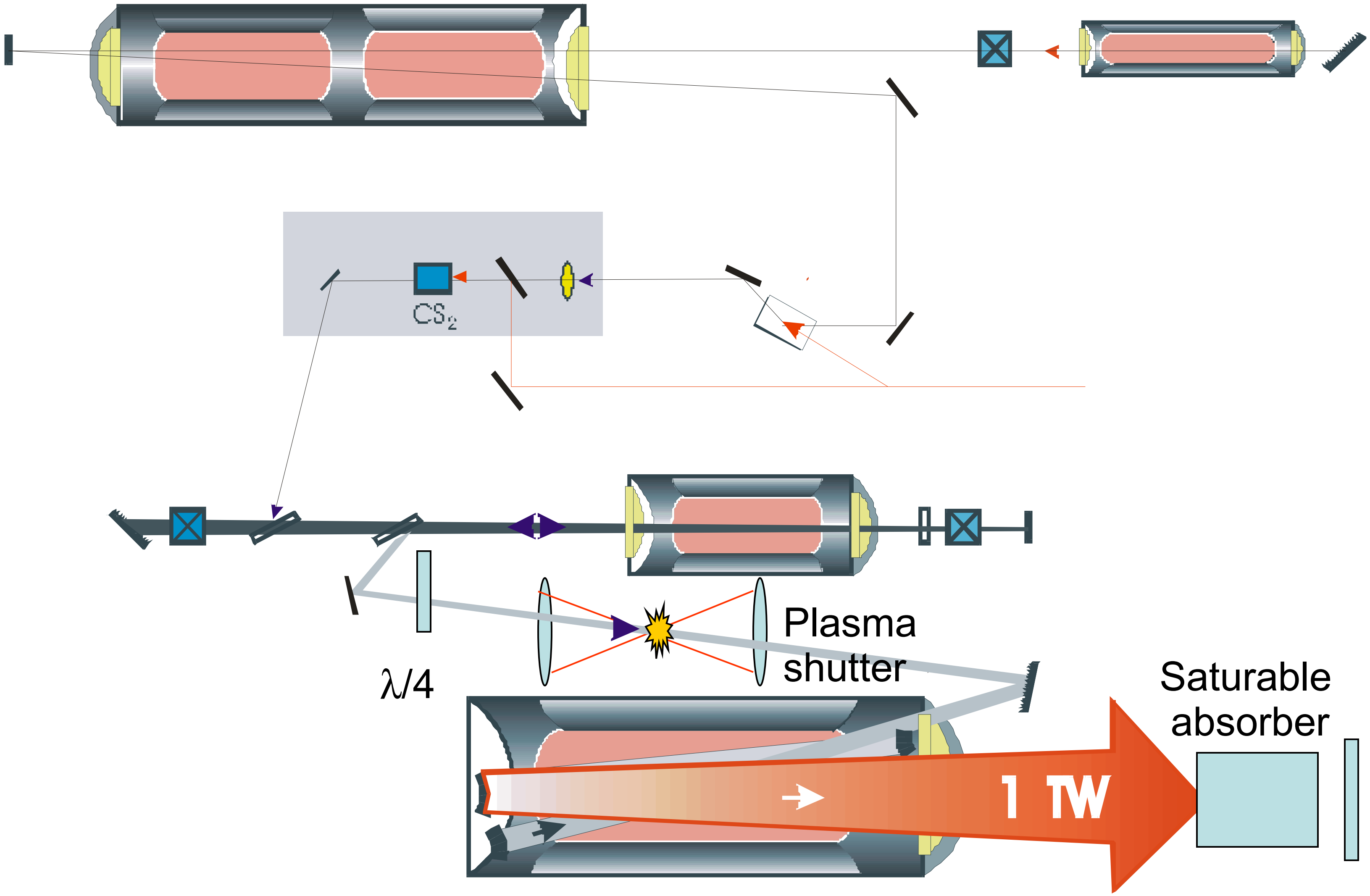
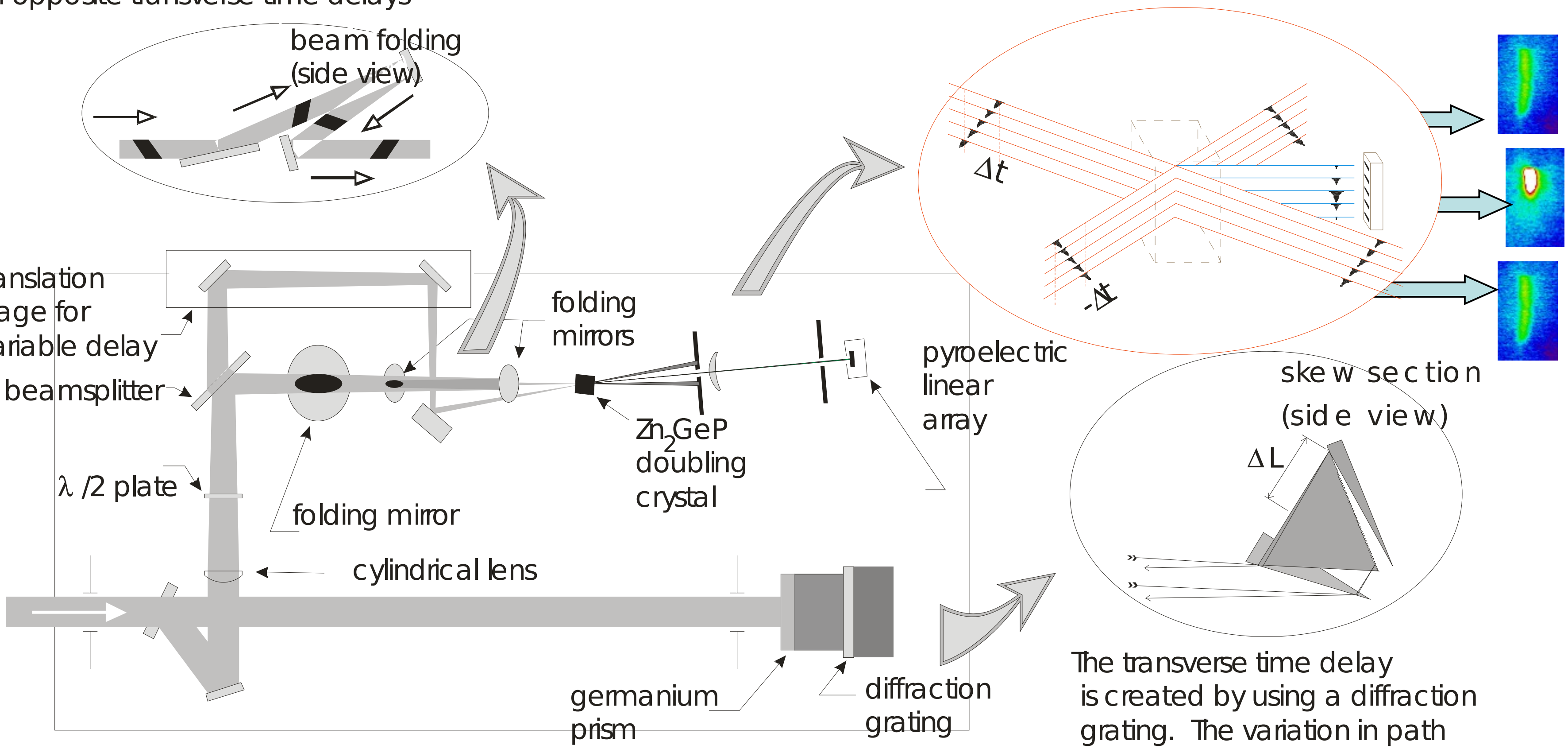
Laser system protection against retroreflection from a target



Single shot autocorrelator

This folding inverts one beam and thereby causes the beams to intersect in the doubling crystal with opposite transverse time delays

single-shot, background-free autocorrelation by non-collinear second harmonic generation



The transverse time delay is created by using a diffraction grating. The variation in path length across the beam produces a total range of $2\Delta L/c$.

CO_2 laser pulse measurements

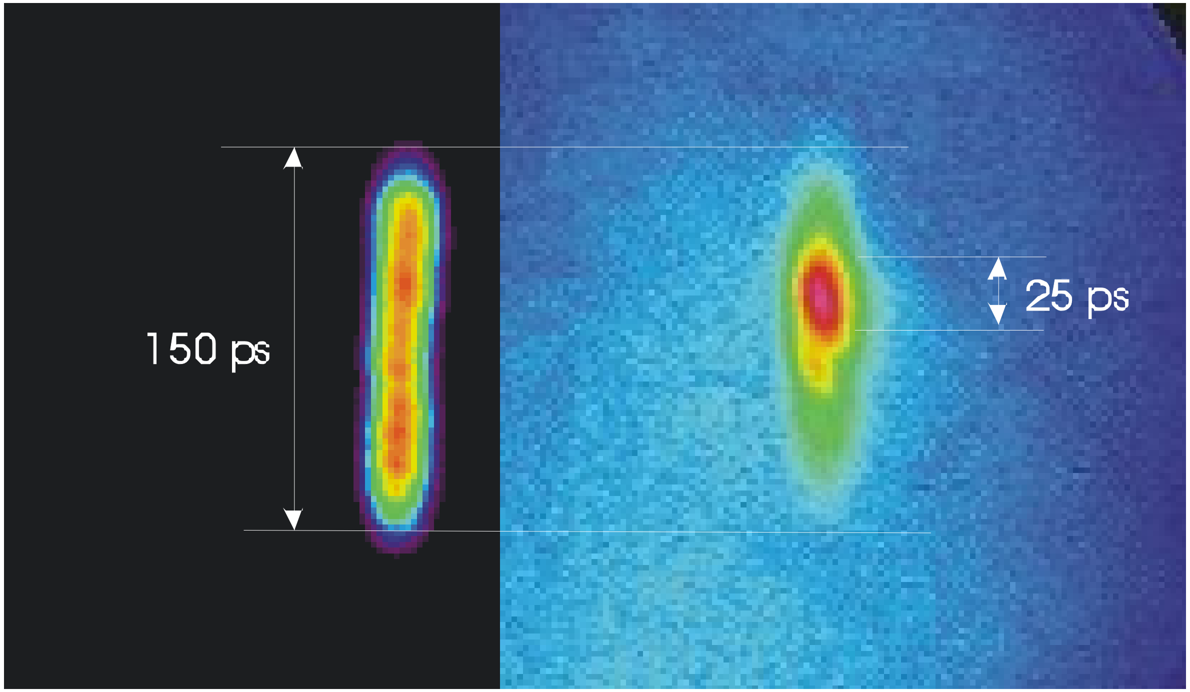
Microbuncher as a CO_2 diagnostic tool

15 ps pulse length is confirmed by time delay scan between the laser and co-propagating 3 ps e-beam while monitoring the IFEL energy modulation

Autocorrelator measurements

Left – intensity distribution in 10 μm fundamental beams across the nonlinear crystal with a real time scale

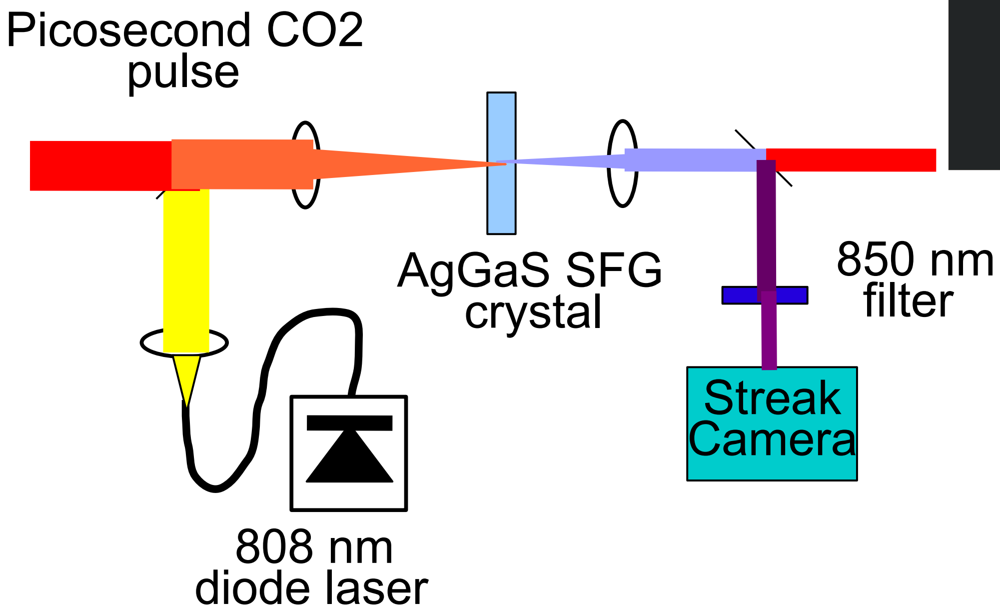
Right – 2^{nd} harmonic signal corresponding to a single-shot autocorrelation function profile

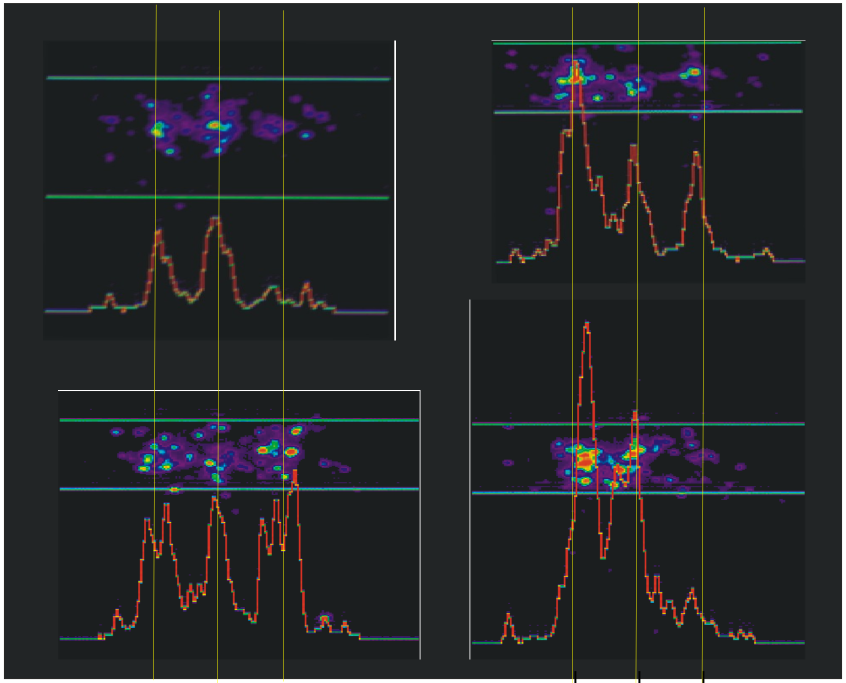


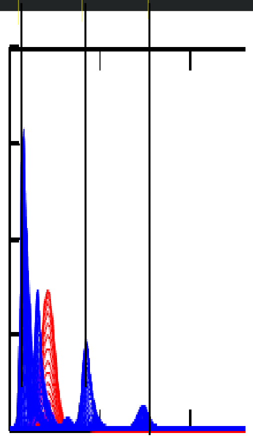
CO2 Pulse Sum Frequency Generation Diagnostic

On-line single-shot temporal diagnostic:

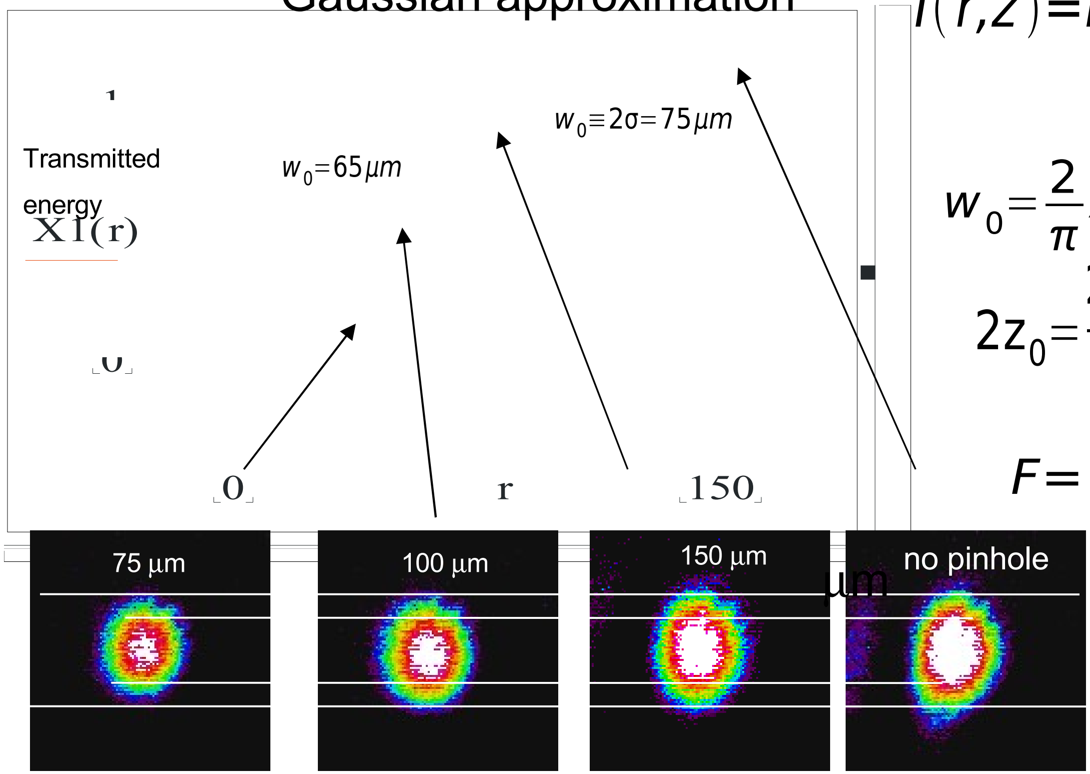
- Allows measurement to resolution of streak camera (~2 ps).
- Already shows structure expected from simulations based on known physics of CO_2 gain medium
- Awaiting more powerful diode laser for better statistics in streak camera







Characterizing the laser focus

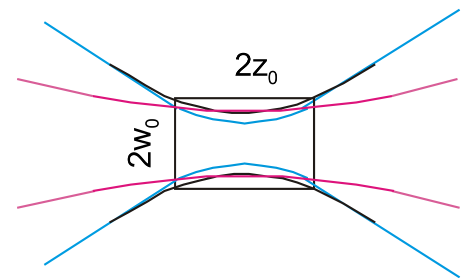


$$I(r,z)=I_0\left[\frac{w_0}{w(z)}\right]^2\exp\left[-\frac{2r^2}{w^2(z)}\right]$$

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

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

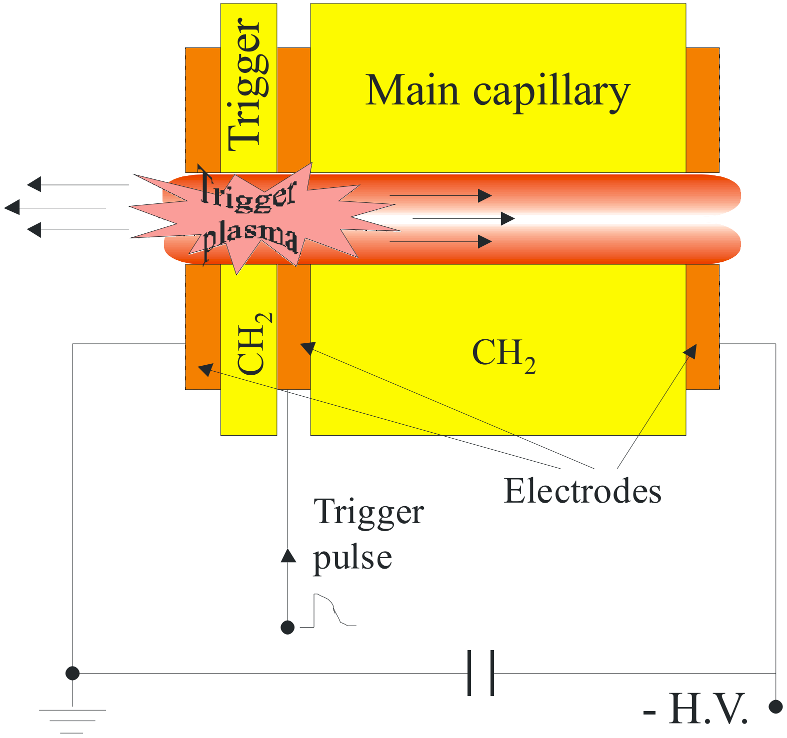
$$F=\frac{f}{D}$$

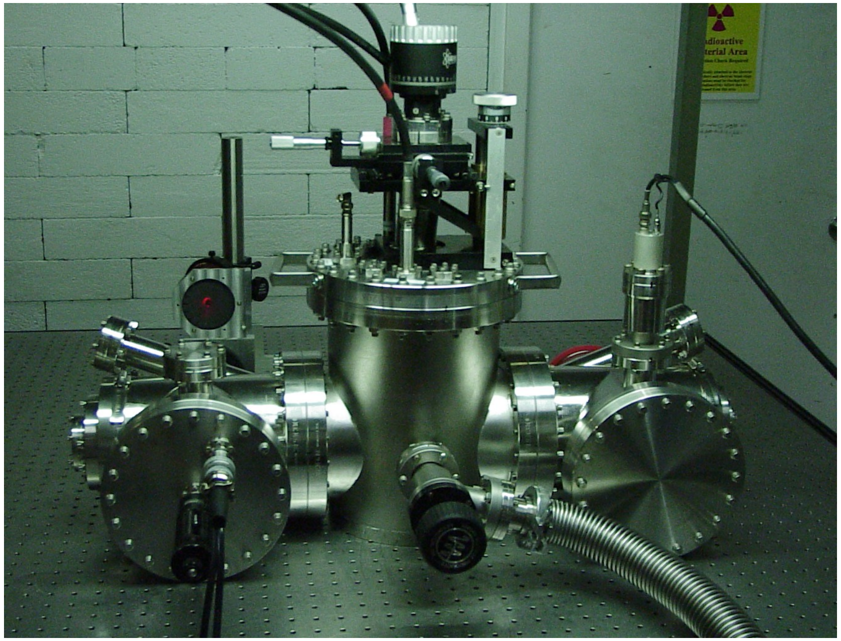


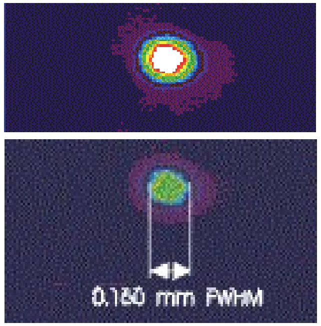
•Laser focus transmitted through pinholes of 75-150 μm dia imaged on IR camera.
Gaussian approximation with w_0=65 μm is the best fit to the observed transmission through pinholes.
For ideal diffraction-limited beam, such focus corresponds to $F_{\#}$=10 and double Rayleigh distance 2.5 mm.
Instead, 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/cm², Target position shall be controlled with 100-200 μm accuracy.

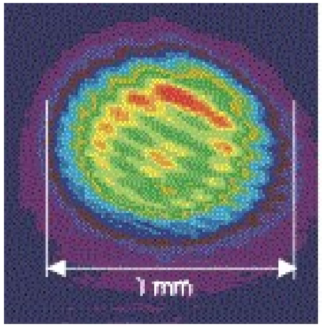
CO_2 laser has been channeled in capillary discharge



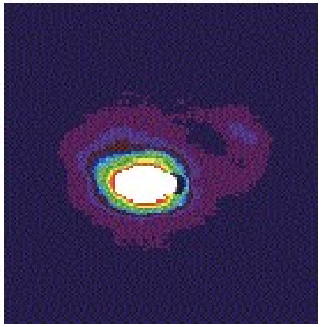




laser beam at the focal point



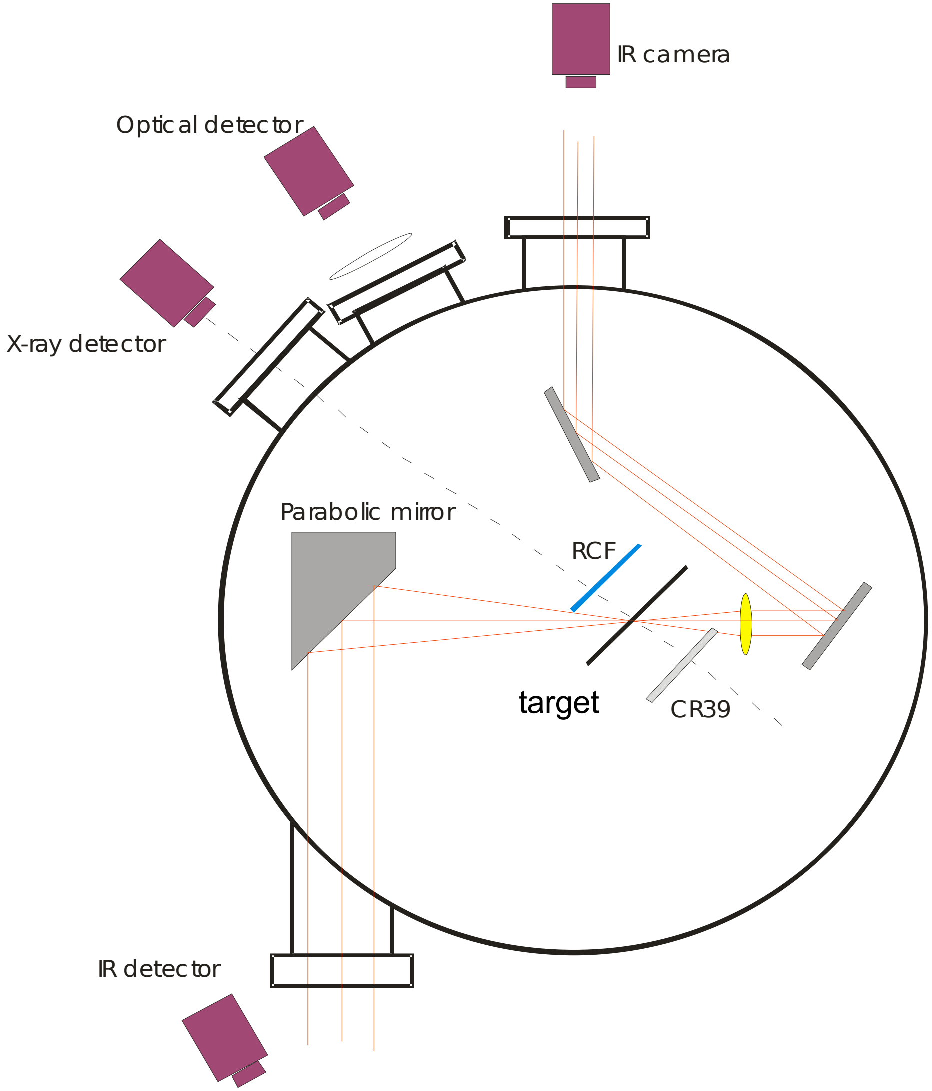
17 mm downstream from the focus in the free space



at the exit from the 17 mm plasma discharge

This enables a new generation of experiments on laser/e-beam interaction in plasma

Layout of a target chamber for ion acceleration experiment

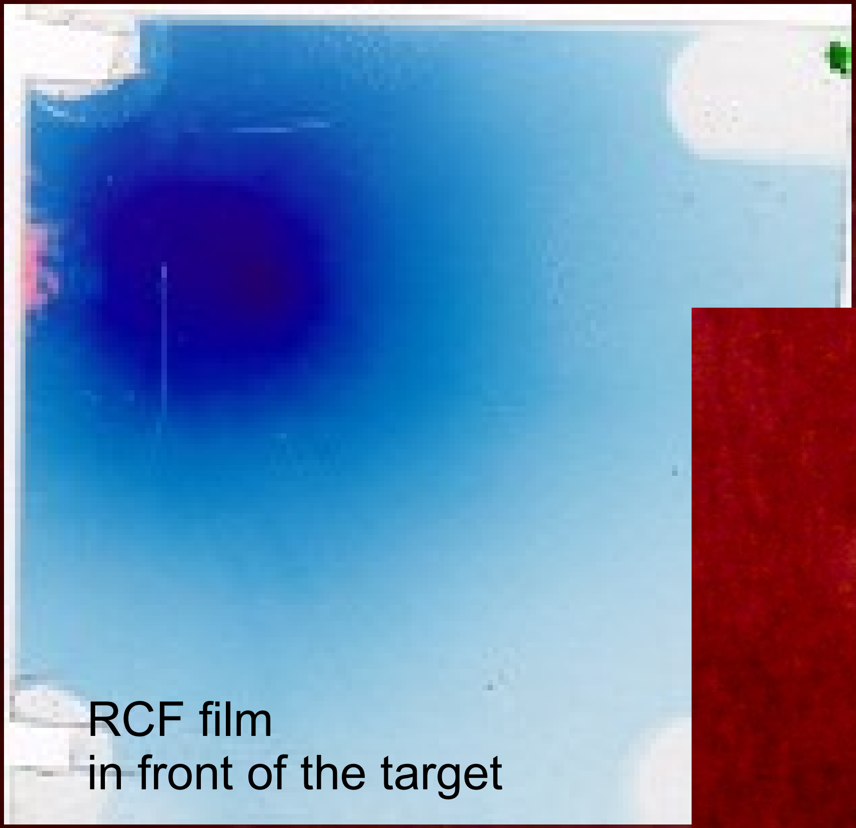


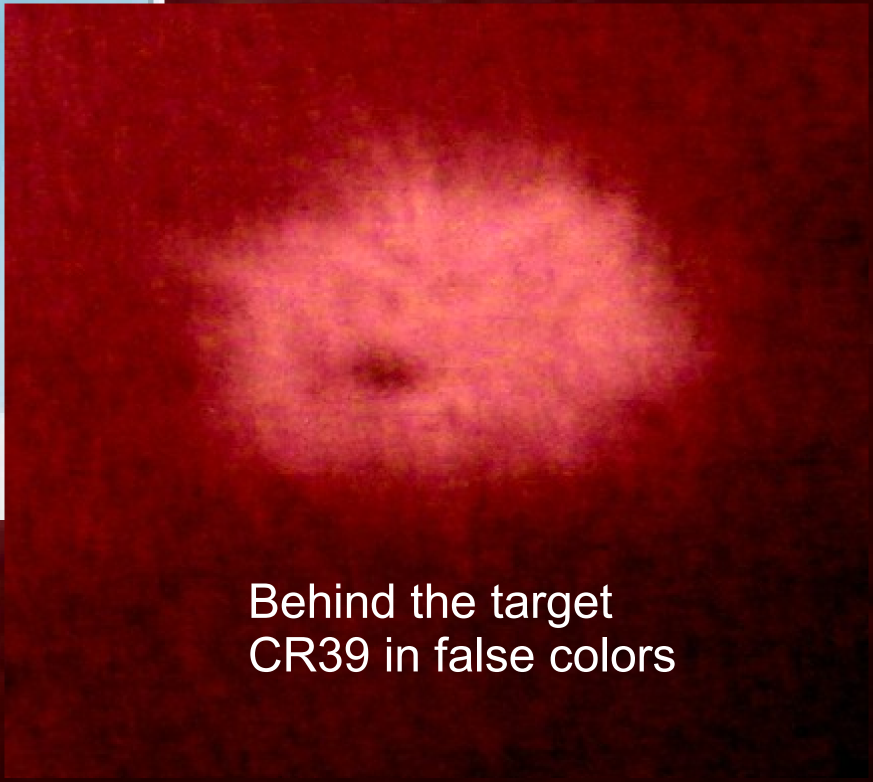
Chamber is normally under 10^{-3} torr.

Parabolic mirror has fine alignment to control aberrations in the focus which is imaged on IR camera with x40 magnification.

Target position is adjusted with a stepper motor. Transverse target motion allows multiple shots without replacing foil.

Signals on x-ray and optical detectors are recorded without RCF.

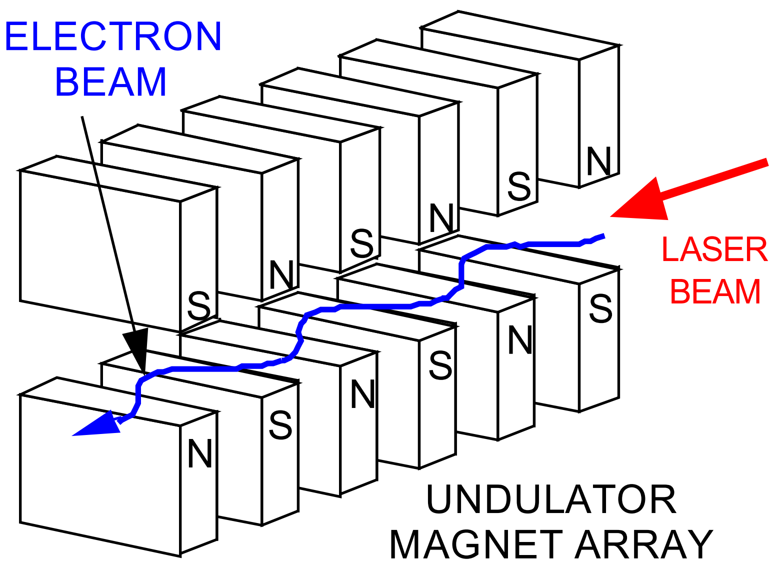




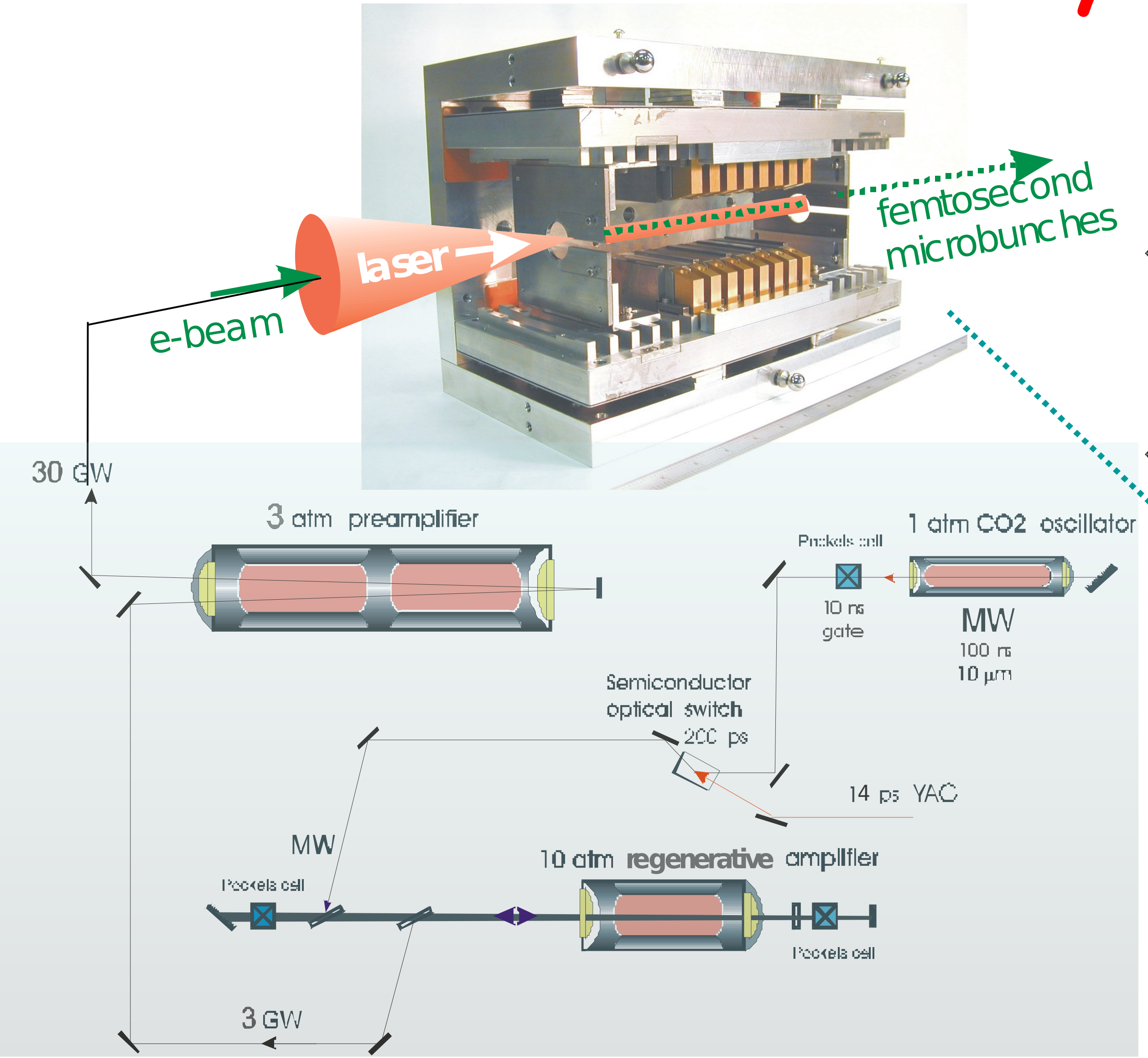
Different structure could be the result of systematic change in laser focus position on the target.

IFEL experiment evolved into "Micro-bunch Factory" enabling a new generation of experiments

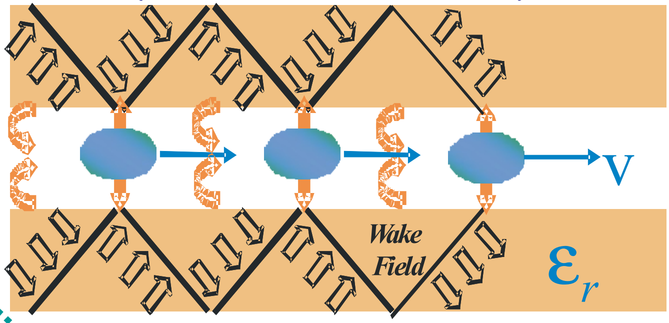
- Resonance PWFA
- Laser pulse length measurement
- STELLA-IFEL (completed)
- PASER



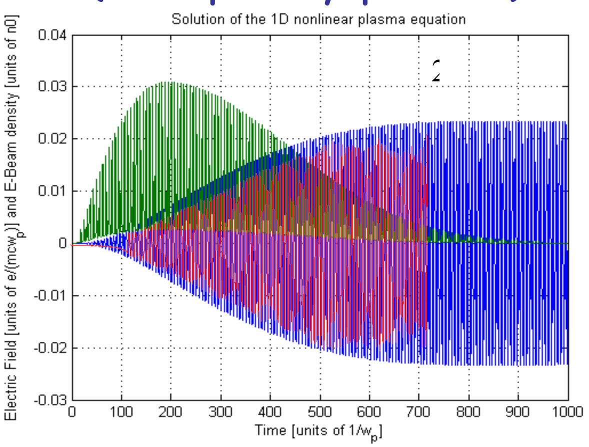
Micro-bunch "factory" (0.3 Hz)



PASER
(in active medium)



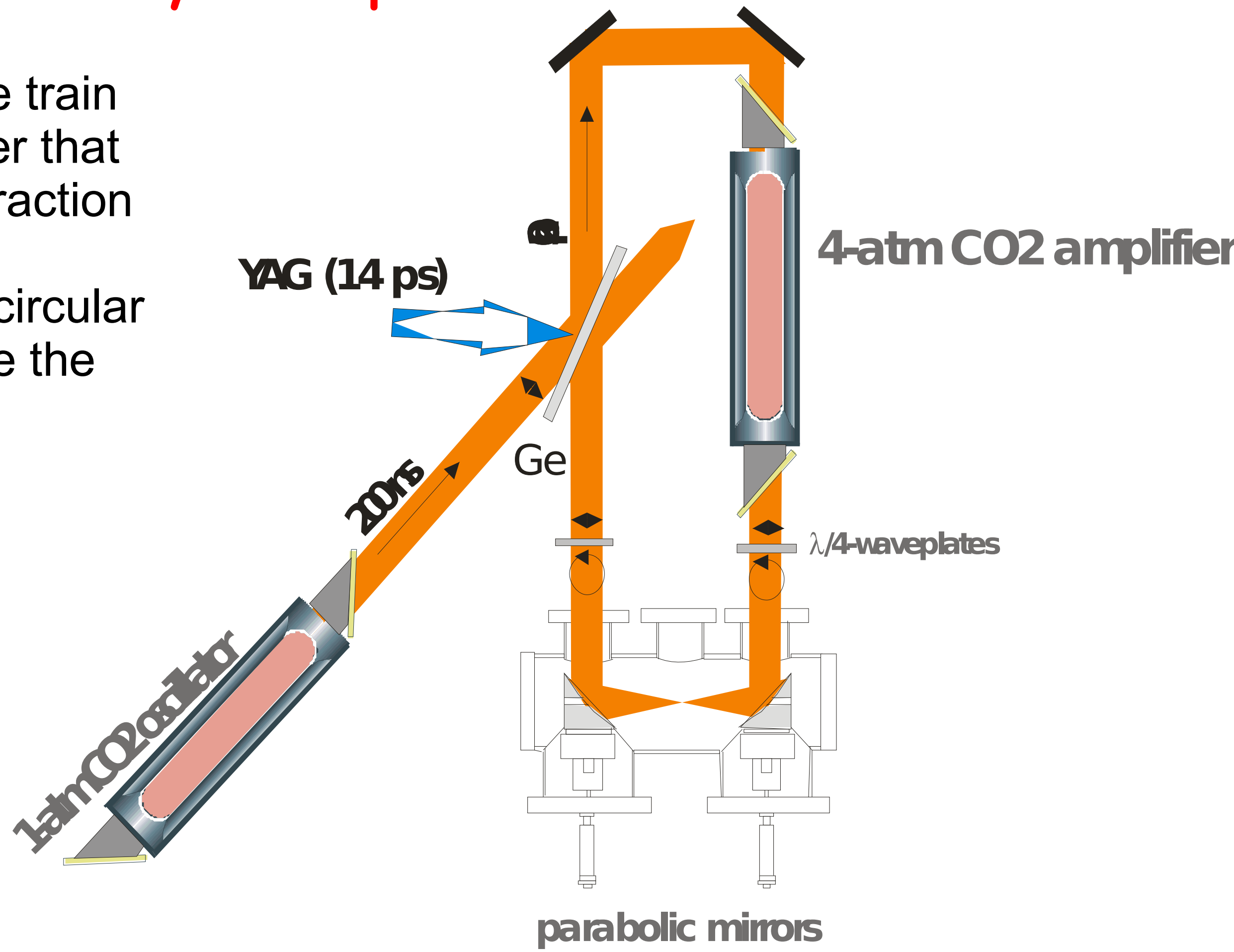
Resonance PWA
(in capillary plasma)



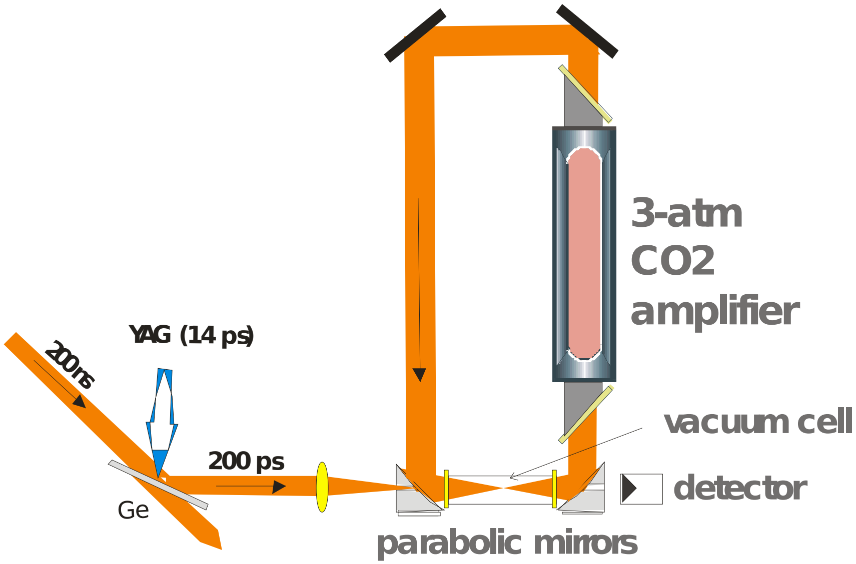
Laser test bench at BNL/ATF for advanced feasibility study of intra-cavity Compton source

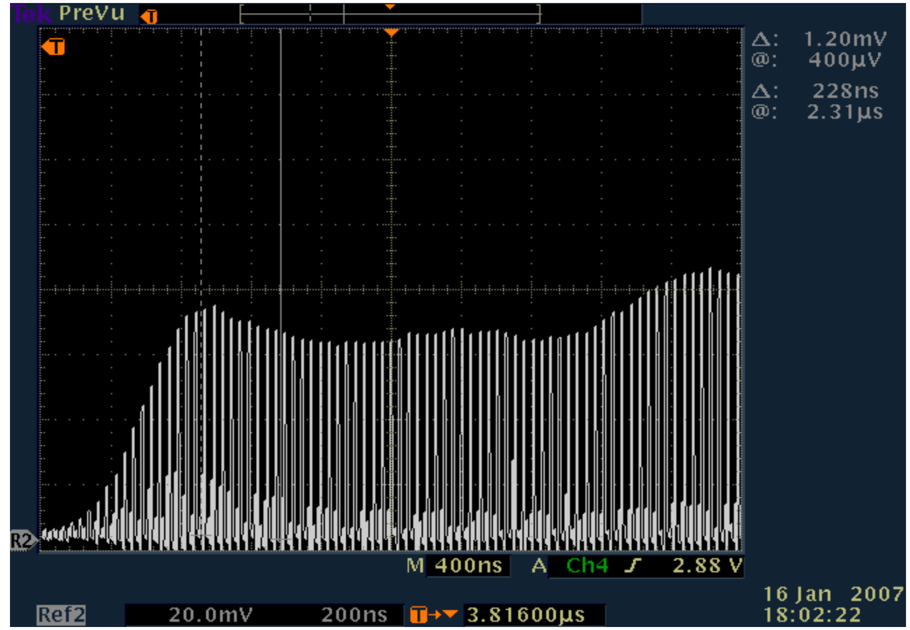
Purpose of the test:

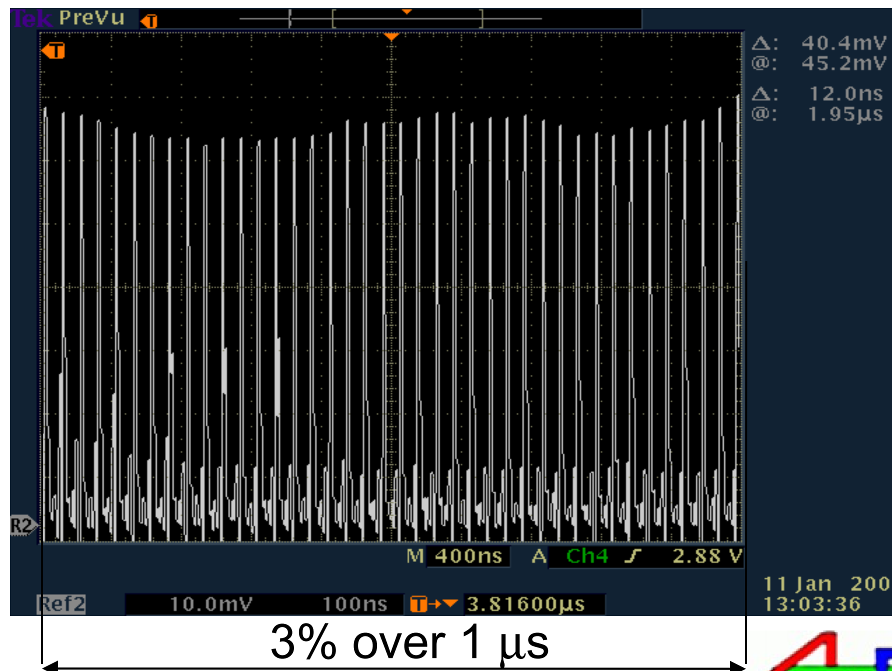
- Demonstration of 100-pulse train inside regenerative amplifier that incorporates Compton interaction point.
- Demonstration of linear-to-circular polarization inversion inside the laser cavity.



Simplified test setup







Observations:

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

Near-future CO_2 laser plans from 2005 (completed)

- Establish 3-ps TW regime of operation for user's experiments.
- Improve and expand on-line laser diagnostics. (Includes CO_2 autocorrelator modification for short-pulse measurement.)
- Develop techniques for isolating the laser system from parasitic feedback (back reflections) from a target plasma.
- Work on characterizing and controlling the contrast.
- Acquire capability for simulating ps pulse amplification.
- Prepare a proposal for a femto-second upgrade.*

Summarizing Progress Since Last Meeting

- Pulse shortening from 25 ps to 5 ps allowed to achieve 1 TW peak power.
- Focusing to w_0=65 μm size, we achieved a_0=0.7.
- After practical realization of a regime with improved high-contrast and parasitic reflections suppressed, the short-pulse laser is applied to user's experiments (nonlinear Thomson, ion acceleration, LWFA).
- Laser is configured for quick switching to a higher-repetition-rate, 200 ps pulse regime to support user's experiments that require microbunching (PASER, resonance PWA).
- New diagnostic and simulation capability allow better characterizing of the laser pulse and support laser development.
- Demonstration of a pulse train inside a picosecond CO_2 laser amplifier supports a new initiative on using intra-cavity gamma source for ILC positron production.

Near-future CO_2 laser plans 2007

- Establish 1-ps multi-TW regime of operation for user's experiments.
- Achieve a_0=2 via higher power and tighter focus.
- Improve diagnostics and modeling to apply to new and potential regimes of operation.
- Continue with highrepetition rate laser R&D closer the ILC requirements.
- Prepare proposal for laser facility to prototype ILC Compton source.
- Prepare a proposal for a femto-second upgrade.