High power laser systems for applications in advanced accelerator research

Csaba Tóth

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Tutorial lecture
NPSS Technology School
July 7, 2001, Snowmass, CO

Who am I? - Who are you?

- ***Csaba Tóth, Ph.D.***

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- ***Talk will also be available on the WEB:***

  http://bc1.lbl.gov/CBP_pages/PEOPLE/Toth/Snowmass2001CPATutorial.html

Goals and approach

- Less **'Why This or That Laser?'** - choice options
- More **'How To?'** - solid-state CPA
- Some **'Who's bigger?'** - examples

- Required knowledge:
  - — Basic optics

- Other detailed laser talks at Snowmass 2001
  - — G. Mourou : ⇒ *July 16, Monday - Workgroup T8*
  - — I. Pogorelski : ⇒ *July 10, Tuesday - Workgroup T8*
  - — S. Tochitsky : ⇒ *July 5 - Workgroup T8*
  - — J. Early : ⇒ *July 6 - Workgroup T1*

Acknowledgment

CPA basics & history, Ti:sapphire case study
Example CPA laser systems
Accelerator applications

Chris Barty	*(LLNL/UCSD)*
Wim Leemans	*(LBNL)*
F. Salin	*(CELIA, France)*
R. Sauerbrey	*(Jena, Germany)*
H. Hutchinson	*(Imperial College, UK)*
C. LeBlanc	*(LULI, France)*
V. Yanowski	*(CUOS, MI)*
M. Downer	*(U.Texas)*
P. Nicklas	*(MBI, Germany)*
T. Ting	*(NRL)*
I. Pogorelski	*(BNL)*
M. Babzien/T. Srinivasan	*(BNL)*
C. Clayton/S. Tochitsky	*(UCLA)*
R. Schoenlein	*(LBNL)*
…	
IEEE-NPSS	*(Bruce Brown)*

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Outline

- **Needs ⇔ Capabilities**
- **Lasers — 102**
- **Amplification principles**
  - **— Chirped Pulse Amplification (CPA)**
- **Case studies**
  - **— multi-TW CPA systems @ LBNL, ex-UCSD**
- **Beam diagnostic tools**
- **Lasers around the globe**
- **Special acceleration related issues, future**

Definition of terms

- **'high power'**
  - **peak: type of induced effects (nonlinearity, direct ionization)**
    - **W, kW, MW, GW, TW, PW**
  - **average: usefulness, yield**
    - **mW, W, kW, MW**

- **'accelerator research'**
  - **wake-field generation**
  - **diagnostics (plasma and beams)**
  - **photocathode**
  - **beam-beam interactions**

Accelerator research ⇔ Sources

Applications / Needed source properties	Wakefield Acceleration	Photo-Cathodes	Beam-beam Interactions	Beam Diagnostics
high peak power	TW	GW	TW, PW	MW
high average power	10s W	W	W, kW	< W
short pulses	fs - ns	fs, ps, ns	fs, ps, ns	fs,ps
synchronization	yes	YES	YES	YES
specific wavelength	800 nm, 10 μm	266 nm	broad	broad
laser type(s)	Ti:sapphire, CO_2, Nd:glass	Nd:YAG, OPO, harmonics	Ti:sapphire, Nd:glass, Yb:S-FAP	all types

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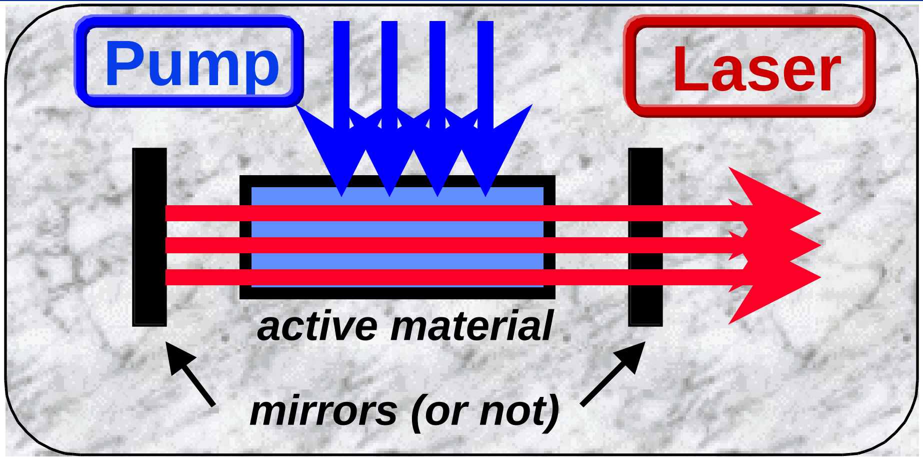
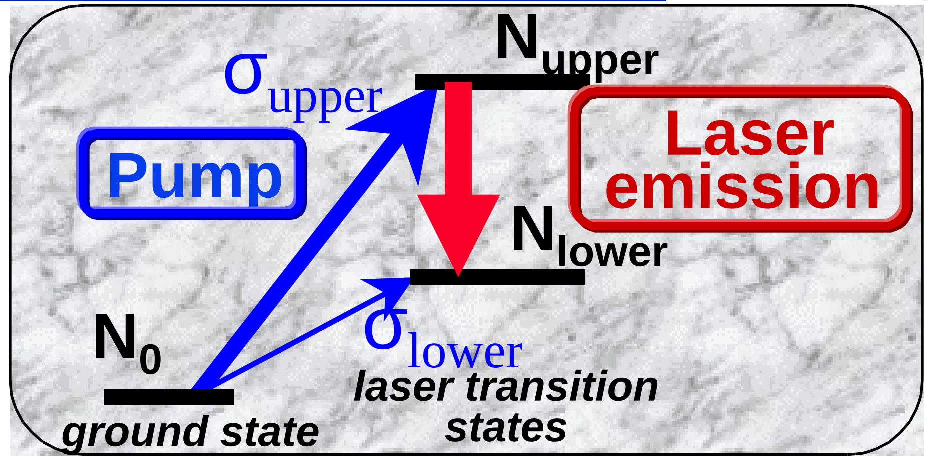
Lasers — 102





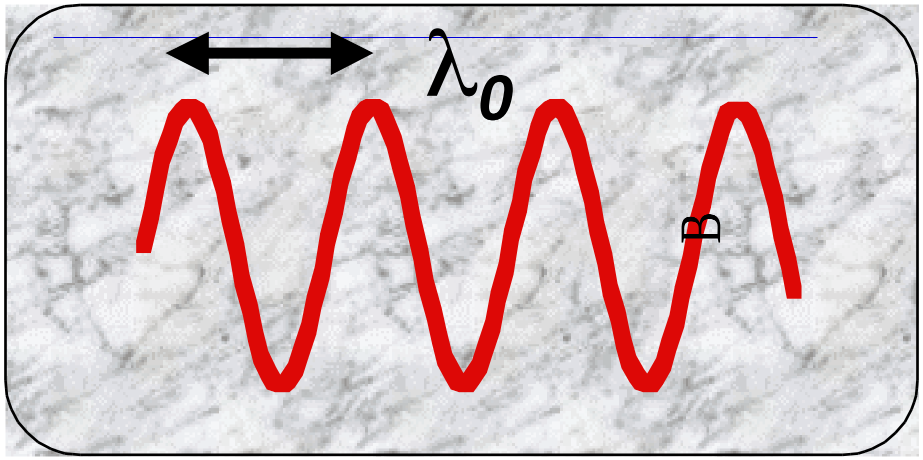
101

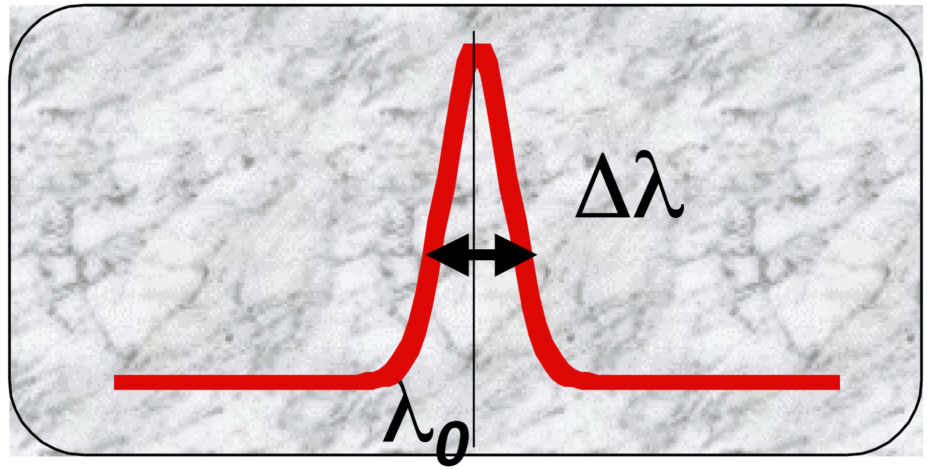
- **Pump**
  - — light (incoherent or other laser)
  - — electrical (discharge, current)
  - — chemical
- **Active material**
  - — solid (Nd:YAG, Ti:sapphire etc. - 'activ ion':'host')
  - — liquid (dyes)
  - — gas (CO_2, KrF, HeNe, etc.)
  - — semiconductor (GaAs, InP, etc.)

Lasers — 102

- **Parameters to be considered**
  - — **Wavelength : λ_0, $\Delta\lambda$**
  - — **Pulse duration: cw, pulsed, rep.rate**
  - — **Spatial properties: focusability, divergence**
  - — **Energy - power**
  - — **Reliability - lifetime - cost (- taste?)** $\Rightarrow$ ***at the end of talk***

Wavelength : λ_0, $\Delta\lambda$





- **Definitions:** $$\lambda_0 = \frac{c}{\nu} = \frac{2\pi c}{\omega_0}$$

$$\Delta\lambda \equiv \text{'}\, bandwidth\text{'}$$

- **Relevance:**
  - — **time-bandwidth product:** $\Delta\nu \cdot \Delta\tau \geq 1$ $\quad \Delta\tau = 1/\Delta\nu = \lambda^2 / c(\Delta\lambda)$
  - — **λ scaling of interactions and structures**

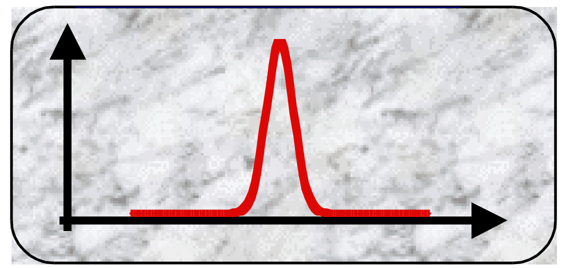
$$e.g.: \quad n_{cr} = \frac{mc^2\pi}{\lambda^2 e^2}, \quad P_{crit} = 17\left(\frac{\lambda_p}{\lambda_0}\right)^2 \text{ [GW]}, \text{ etc.}$$

Time: cw, pulsed, rep.rate

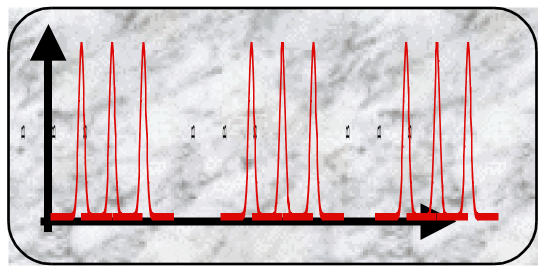
- **Continuous wave - cw**

- **Pulsed - normal, Q-switch, Mode-Locking (ML)**

  ~μs ~ns ~ps, ~fs



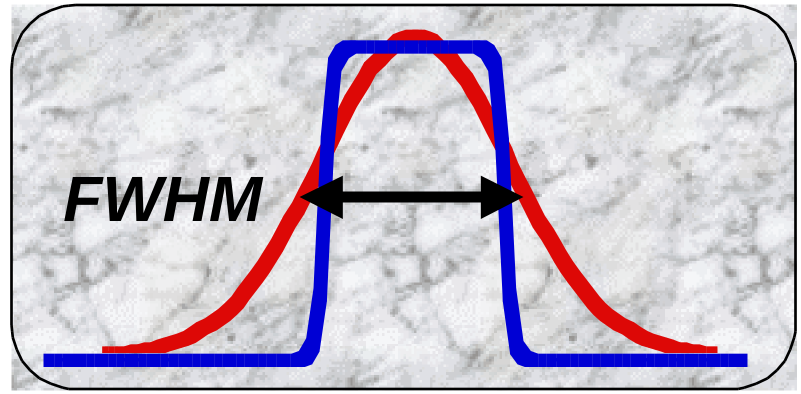
- **Burst modes**



- **<u>Relevance:</u>**
  - — synchronization
  - — matching to micro-/macro-pulse structure
  - — dynamics of interactions, bunch length

Space: spot size, divergence

- **Intensity distribution perpendicular to the propagation axis**
  - — 'top hat'
  - — Gaussian



- **Divergence determines the focusability - Gaussian beams**

$$w^2(z) = w_0^2 + (\lambda/\pi w_0)^2 (z - z_0)^2$$

$$z_R \equiv \pi w_0^2/\lambda, \quad \textit{Rayleigh length}$$

- **Relevance:**
  - — focusability
  - — matching to particle beams, overlap
  - — channel guiding

Energy & power

- **Definitions**

  Energy: total # of available photons

  Power: how concentrated are they

  … in time

  Intensity: … and in space

$$E = (\#) \times h\nu \quad [\text{eV}]; \quad [\text{Joule}]$$

$$P = \frac{E}{\tau} \qquad \left[\frac{\text{J}}{\text{s}}\right] = [\text{Watt}]$$

$$I = \frac{P}{A} \qquad \left[\frac{\text{Watt}}{\text{cm}^2}\right] = [\text{W/cm}^2]$$

- **Examples:**

  500 mJ energy in λ=800 nm ($h\nu$ = 1.55 eV) photons **# = 10^{19}**

  in 50 fsec pulse: **P = 10^{13} W = 10 TW**

  in a spot of 6 μm diam.: **I = $3 \cdot 10^{19}$ W/cm^2**

  Field strength:

$$\vec{E}_{[\text{V/cm}]} = 27 \times \sqrt{I_{[\text{W/cm}^2]}}$$

- **Relevance:**

  — **attainable/avoidable nonlinear processes**

  — **yield of final products**

  — **efficiency**

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Amplification principles

— Saturation fluence, gain

— Multi-stage amplifiers

— Damage thresholds

— Stretching in space: beam expanders

— Stretching in time: CPA

Chirped Pulse Amplification

Amplification principles — gain

Single pass amplification determined by saturation fluence:

Small signal gain per pass:

$$G = \exp\left(\frac{J_{sto}}{J_{sat}}\right)$$

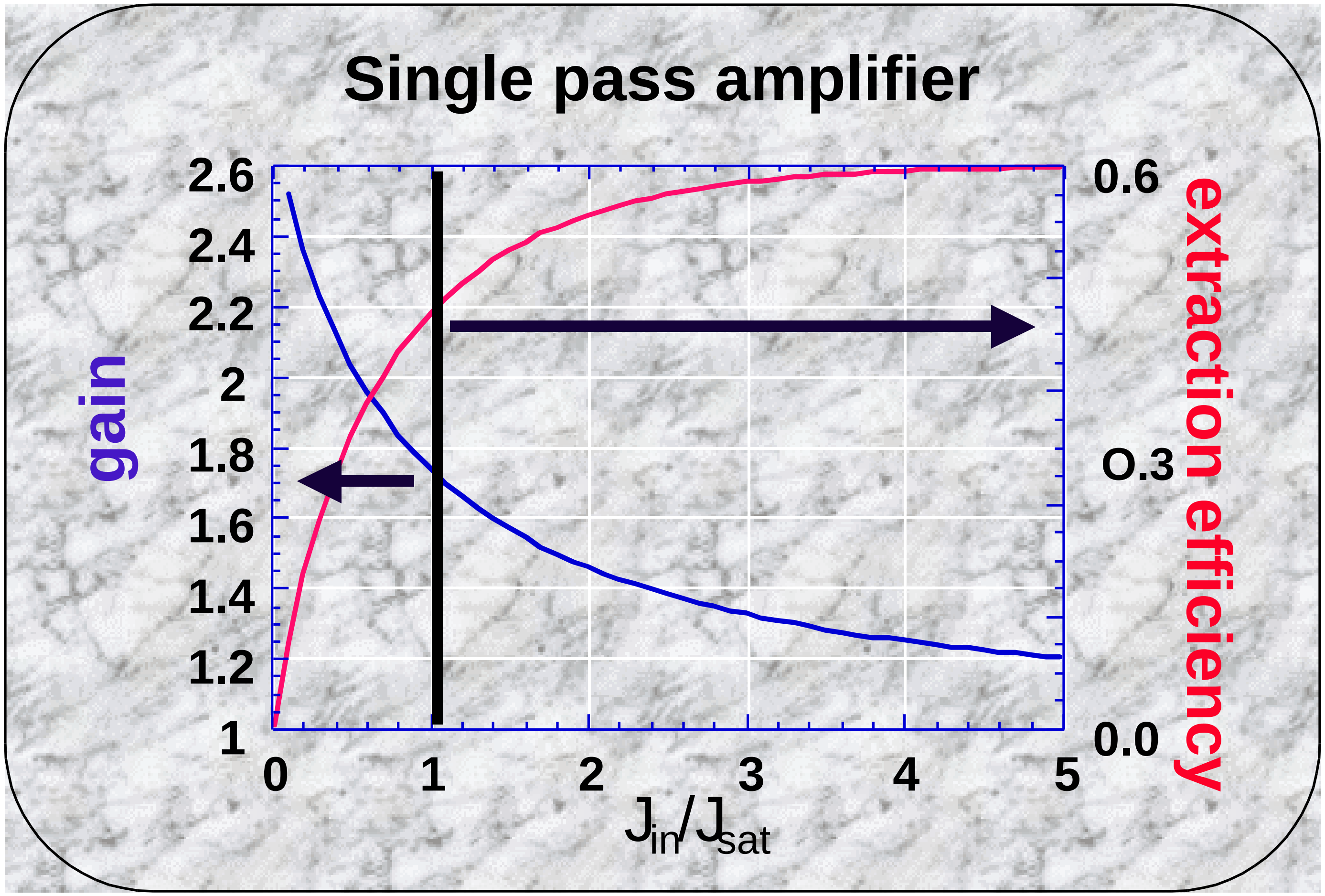
Saturated gain: Frantz-Nodvick equation:

$$J_{out} = J_{sat} \log\left[G_0\left\{\exp\left(J_{in}/J_{sat}\right) - 1\right\} + 1\right]$$

Laser media, a comparison

	J_{sat}	gain 1J/cm² stored energy
Dyes	1 mJ/cm^2	>10 ^{60}
Excimeres	1-10 mJ/cm^2	10 ^{43}
Nd:YAG	500 mJ/cm^2	7.5
Nd:glass	5 J/cm^2	1.22
Ti:sapphire	1 J/cm^2	2.7
Alexandrite	22 J/cm^2	1.05

Amplification principles — gain curves



We must operate close to J_{sat} for maximum efficiency but far from J_{sat} for high gain.

Amplification principles — multi-stage

Net gain : 10^8 $\Longrightarrow$ in single pass impossible

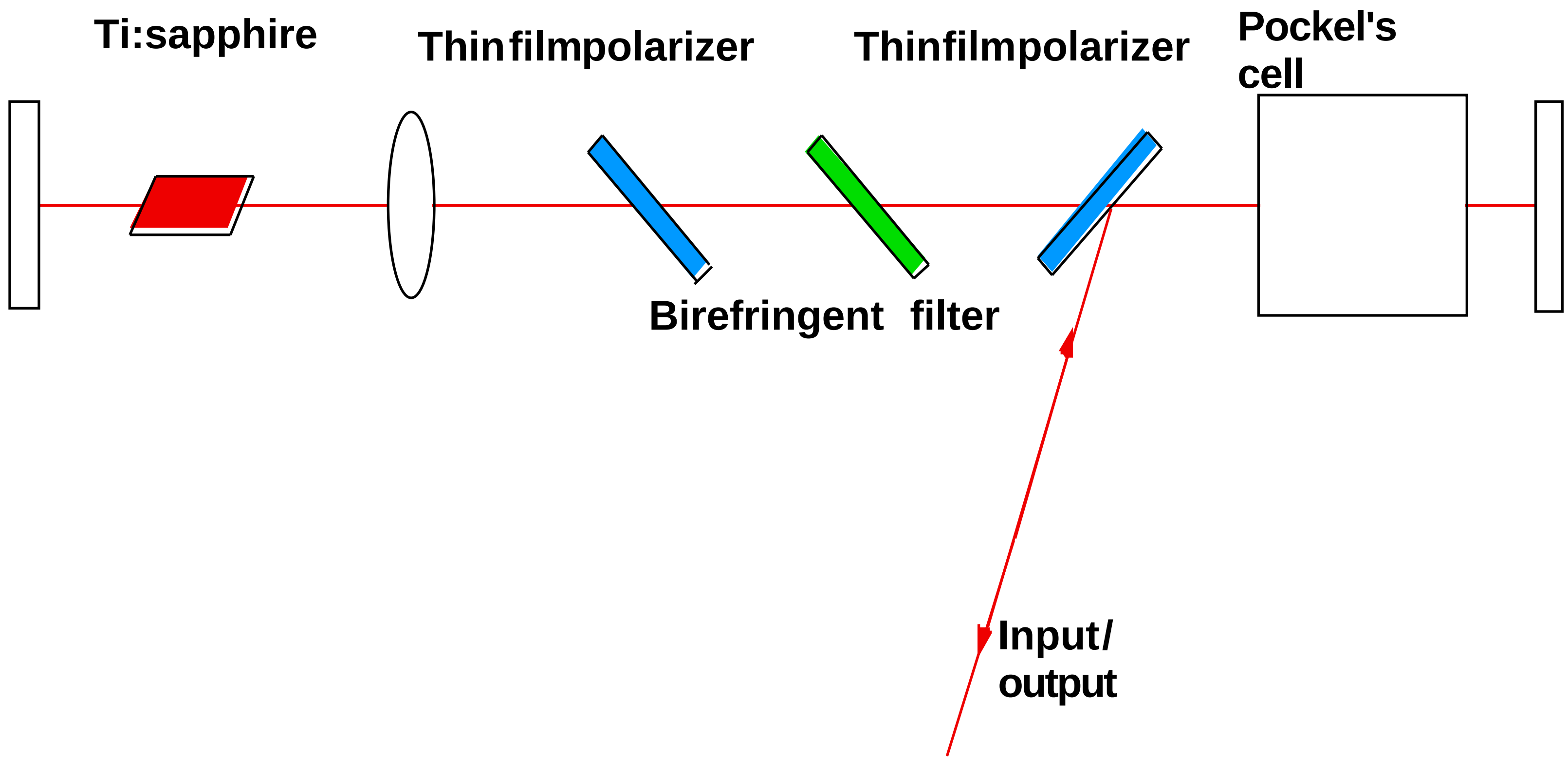
High gain and large extraction efficiency within the same stage is difficult

$\Downarrow$

Multi-stage, multi-pass amplifiers

High gain pre-amplifier + low gain saturated power amplifier

Ti:sapphire regenerative amplifier



Regenerative amplifier

Advantages:
- very good beam quality
- works with low gain media
- regenerative gain shaping

Drawbacks:
- losses gain narrowing
- large material thickness
- prepulses

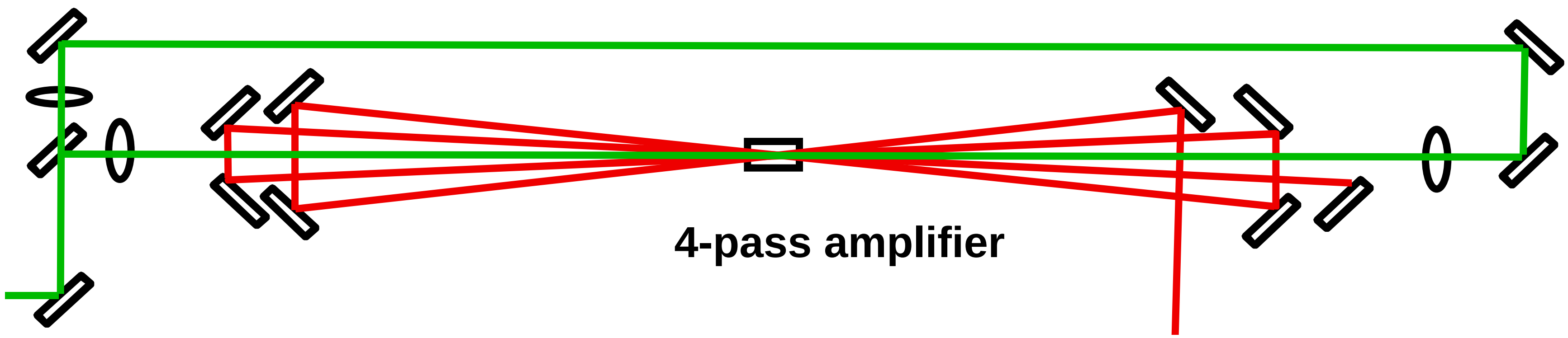
$G_0 = 2$ per pass $\quad J_p \approx 1\, J/cm^2 \quad \approx 300\ \mu m$

Saturation ($J_{in} > J_{sat}$) is never reached in a regenerative amplifier

Gain reduction arises from depopulation

same gain for ASE and pulse

Multipass amplifier



Advantages: - low loss smaller gain narrowing
- no prepulses
- small material thickness

Drawbacks: - high saturation
- needs high gain material
- beam quality sensitive to alignment

The Solid State Amplifier Problem

$$I_{max} >> I_{damage}$$

$$I_{max} \sim F_{sat}/\Delta t_{min} \sim 10^{12} \text{ to } 10^{14} \text{ W/cm}^2$$

(output intensity from final amplifier)

$$I_{damage} \sim 5 \times 10^9 \text{ W/cm}^2 \text{ @ 1 ns}$$

(dielectric breakdown limit)

- Make the amplifier diameter big to decrease intensity
  — Energy extraction is very inefficient
- Disperse the pulse in time to decrease intensity
  — Chirped Pulse Amplification

Maximum Intensity at Saturation

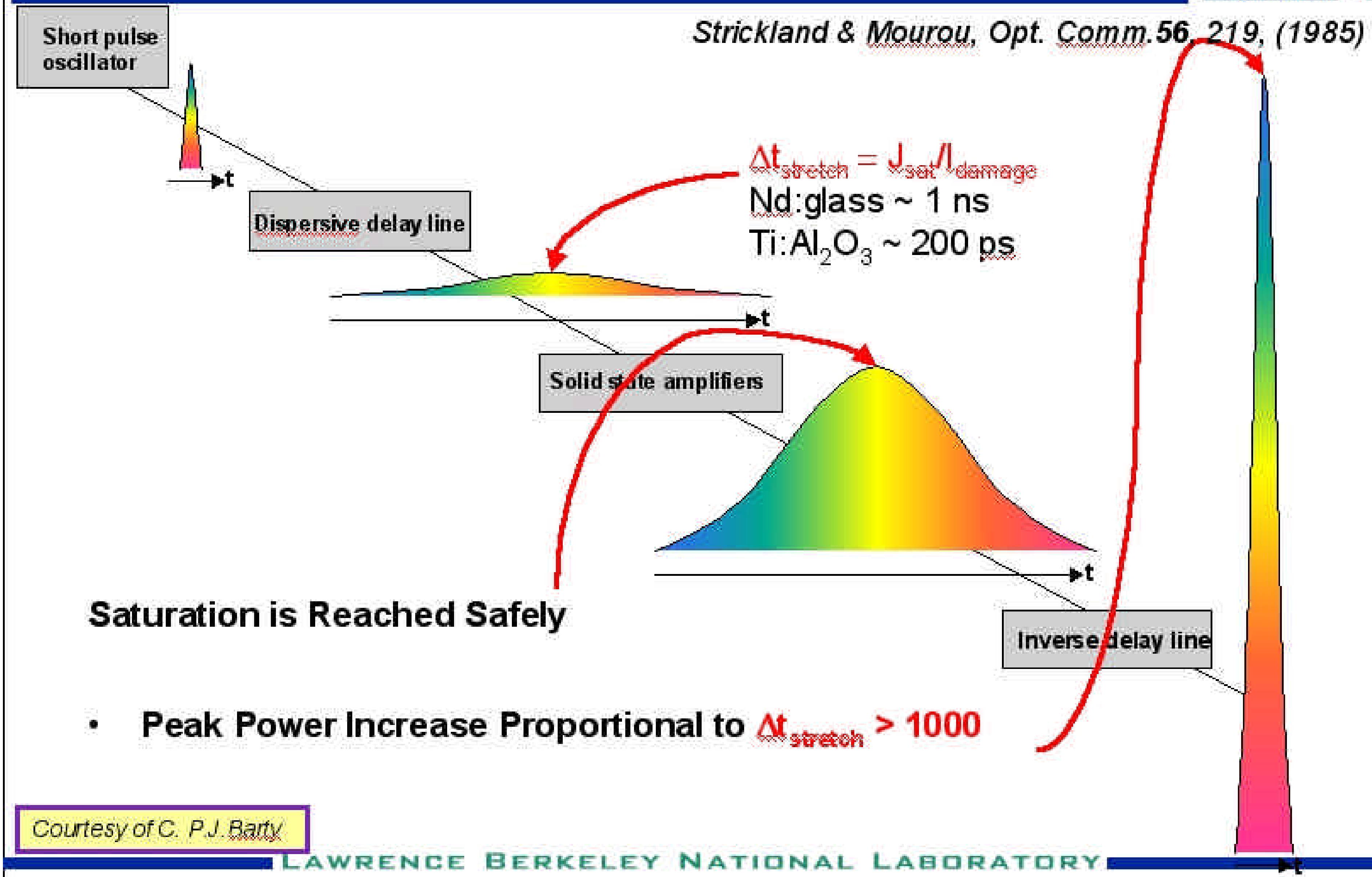
Material	J_{sat} (J/cm^2)	Δt_{min} (fs)	I_{max} (W/cm^2)
Nd:Silicate	6	60	10^{14}
Yb:Silicate	32	20	1.6×10^{15}
Ti:Sapphire	1	3	3.3×10^{14}

ALL >> 5×10^9 W/cm^2

Conclusion:
We must reduce pulse
INTENSITY
during amplification

Generic Chirped Pulse Amplification

Strickland & Mourou, Opt. Comm. ***56****, 219, (1985)*



Saturation is Reached Safely

- **Peak Power Increase Proportional to $\Delta t_{stretch}$ > 1000**

Courtesy of C. P.J. Barty

Nd:glass systems properties

- Energy storage good
  - $J_{sat} = 7\ J/cm^2$
- Pumping straightforward
  - 400 microsecond lifetime easily flashlamp pumpable
- Dispersion control less of an issue
  - Picosecond pulses require only GDD and maybe cubic compensation
- Repetition limited
  - Thermal loading a problem. Must wait to re-equilibrate
- Pulse duration limited to around a picosecond
  - Typically 300 fs to 1 ps

Ti:sapphire fs systems properties

- **Sapphire great optical quality, high damage threshold**
  - **— Also superior thermal material. Sapphire is often used as transparent heat sink**
- **Ideal saturation fluence**
  - **— J_{sat} = 1 J/cm^2 yields a stretching requirement of only 200 ps**
- **Huge bandwidth**
  - **— Theoretically could support 3 fs pulses**
- **Short lifetime**
  - **— 3 ms requires laser pumping or heroic flashlamp circuitry**

UCSD Multi-Terawatt Laser Systems

- **High-order phase compensation**
  - B. E. Lemoff and C. P. J. Barty, Opt. Lett, 18, 1651-1653, (1993)
  - J. Squier, C. P. J. Barty, F. Salin, C. Le Blanc and S. Kane, Applied Optics, (1998)
  - D. N. Fittinghoff, B. C. Walker, J. A. Squier, C. S. Toth and C. P. J. Barty, JSTQE, 4, 2,430 - 440, (1998)

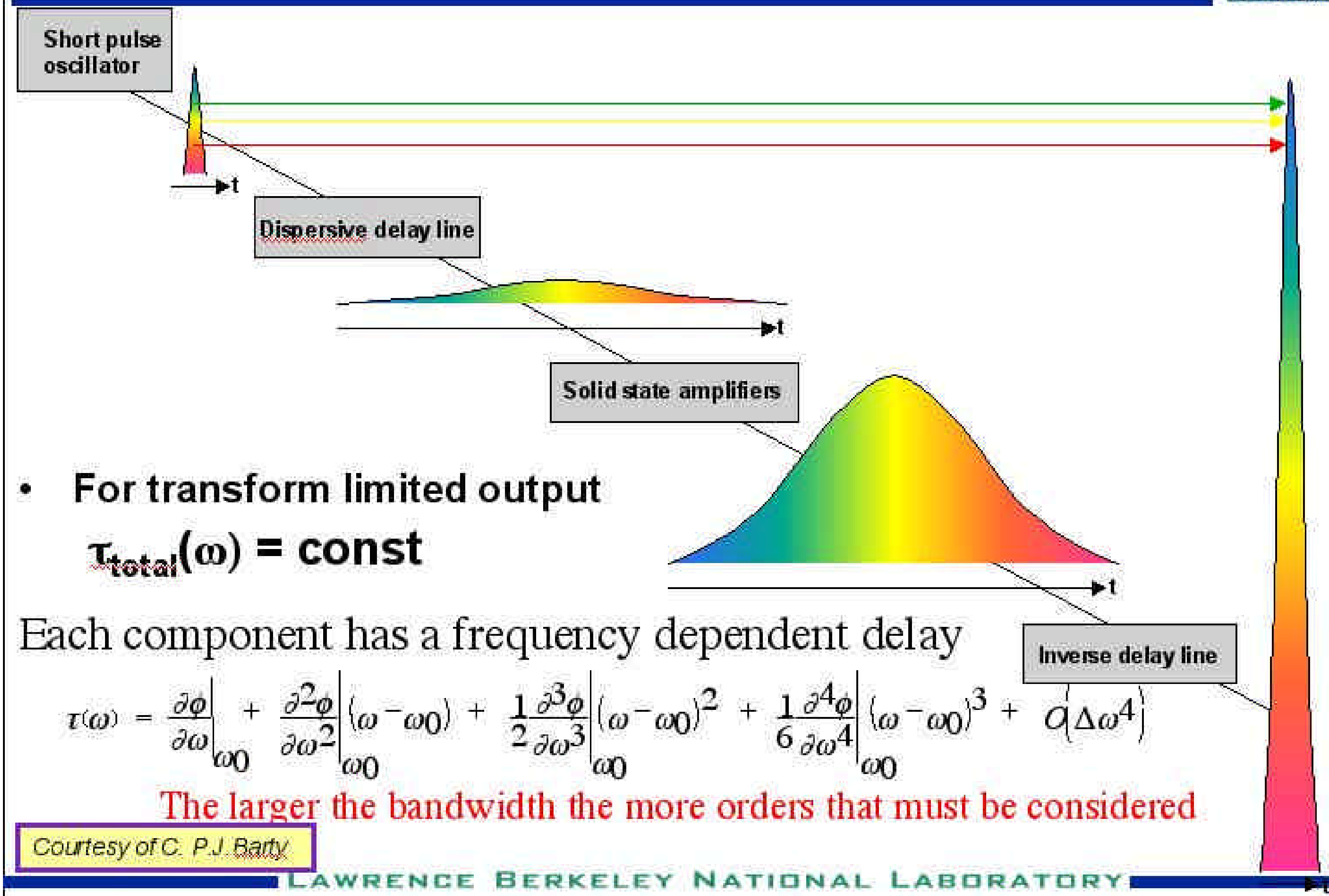
- **Regenerative pulse shaping**
  - C.P.J. Barty, G. Korn, F. Raksi, C. Rose-Petruck, J. Squier, A. -C. Tien, K. R. Wilson,
  - V. V.Yaklovev and K. Yamakawa, 20, B. 13, 219-221, (1996)
  - A. K. Hankla, A. B. Bullock, W. E. White, J. A. Squier and C. P. J. Barty, Opt. Lett., (1997)

- **Energy extraction optimization**
  - C. P. J. Barty, T. Guo, C. LeBlanc, F. Raksi, C. Rose-Petruck, J. Squier, K. R. Wilson, V. V.Yakovlev and K. Yamakawa, Opt. Lett., 21, 668, (1996)
  - K. Yamakawa, M. Aoyama, S. Matsuoka, H. Takuma, D. N. Fittinghoff and C. P. J. Barty, JSTQE 4, 2, 385 (1998)

- **Thermal compensation**
  - F. Salin, C. Le Blanc, J. Squier and C. P. J. Barty, Opt. Lett., 23, No. 9, 718 - 720, (1998)
  - C. Le Blanc, F. Salin, J. Squier, C. P. J. Barty and C. Spielmann, JSTQE 4, 2, 407, (1998)

- **Novel pulse measurement technologies**
  - David N. Fittinghoff, Jeff A. Squier, C.P.J. Barty, John N. Sweetser, Rick P. Trebino and Michiel Müller,Opt. Lett., 23, 13, (1998)
  - J. A. Squier, D. N. Fittinghoff, C. P. J. Barty, K. R. Wilson, M. Müller and G. J. Brakenhoff, Opt. Comm.(1997)
- **Hybrid vacuum-atmosphere compressors**
  - B. Walker, J. Squier, D. Fittinghoff, C. Rose-Petruck and C. P. J. Barty, JSTQE, 4, 2, 441 - 444, (1998)

Phase Distortions & Transit Time



- **For transform limited output**

  $\tau_{total}(\omega)$ **= const**

Each component has a frequency dependent delay

$$\tau(\omega) = \left.\frac{\partial\phi}{\partial\omega}\right|_{\omega 0} + \left.\frac{\partial^2\phi}{\partial\omega^2}\right|_{\omega 0}(\omega-\omega 0) + \frac{1}{2}\left.\frac{\partial^3\phi}{\partial\omega^3}\right|_{\omega 0}(\omega-\omega 0)^2 + \frac{1}{6}\left.\frac{\partial^4\phi}{\partial\omega^4}\right|_{\omega 0}(\omega-\omega 0)^3 + O(\Delta\omega^4)$$

The larger the bandwidth the more orders that must be considered

Courtesy of C. P.J. Barty

Conventional CPA Expander/Compressor

Δt = 300 ps

G D D

3,000,000 fs^2

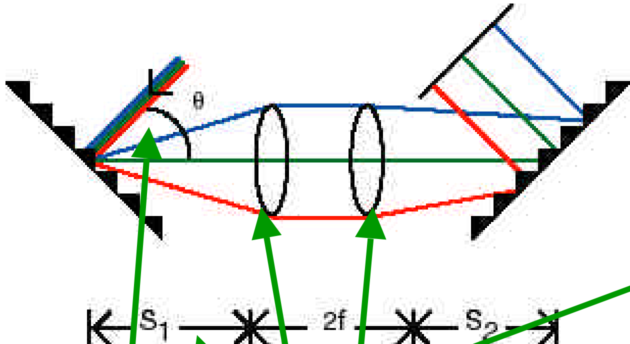
Cubic

4,800,000 fs^3

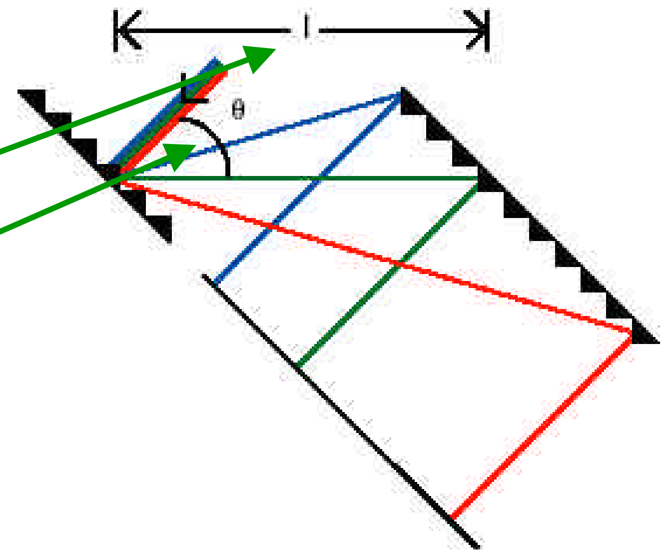
Quartic

9,800,000 fs^4

Positive dispersion expander



Negative dispersion compressor



Dispersion is Matched IF and ONLY IF

- $l = 2f - s_1 - s_2$
- $\theta_{ex} = \theta_{comp}$
- lenses are paraxial
- NO material in the system

BUT 1 mm BK7 or a GDD of 50 fs^2/rad will broaden a 10-fs pulse to 20 fs

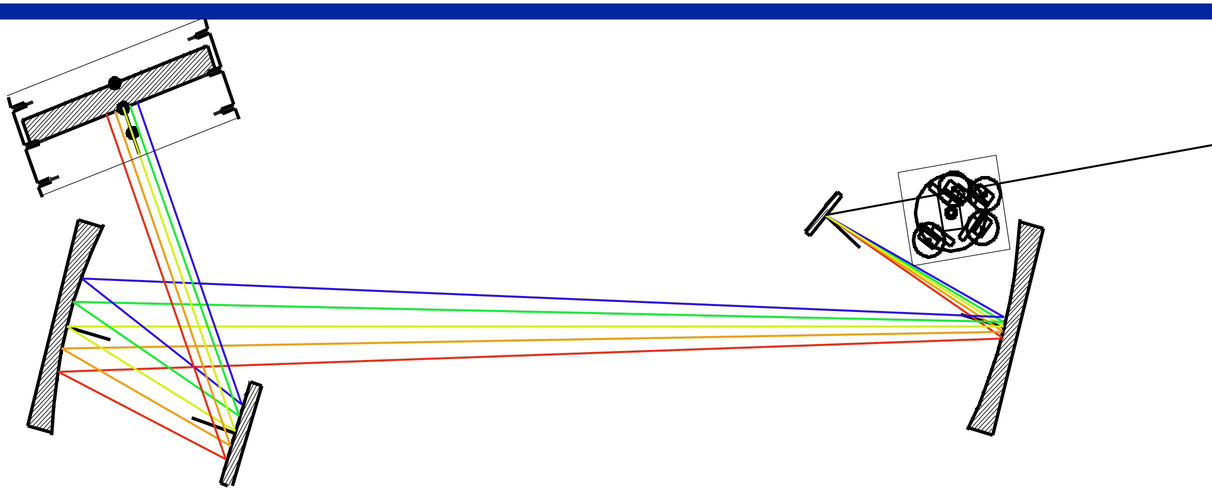
Small Mismatch = BIG ERROR

Conventional CPA Devices

- **If the effect of 2nd order >> 3rd order >> 4th order etc.**
  - **Then we only need to correct for up to 5th order in phase for 15 fs pulses**

- **5th order limited approaches**
  - **Cylindrical Mirror Based Expander (Stanford, UCSD, JAERI, Max Born, Positive Research)**
  - **Mixed Grating Expander and Compressor (UCSD, ENSTA, Positive Light)**
  - **Air Spaced Doublet Expander (LLNL)**
  - **Abberation-free Expander, Minimal Material + Additional Prism Pair (CUOS)**

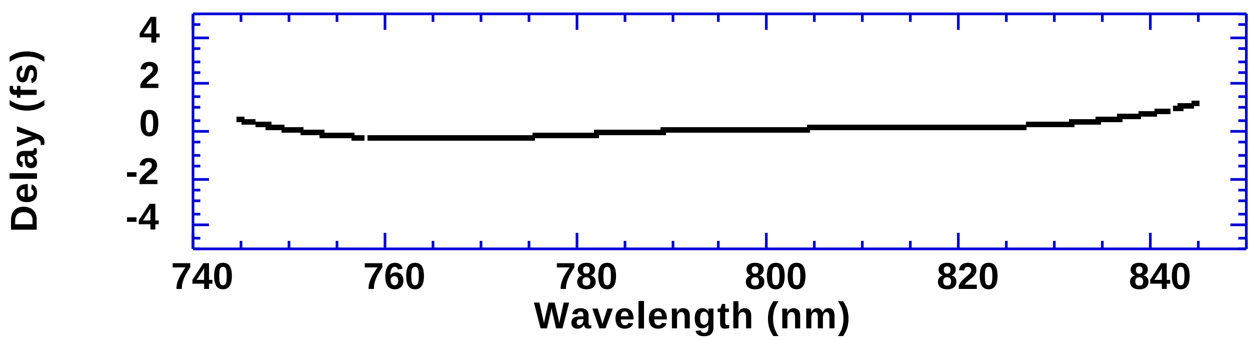
Cylindrical Mirror-based Expander



- **Spherical aberrations allow control of up to quintic phase delays**

100,000 x's stretching and >1 m material path = efficiency and scalability

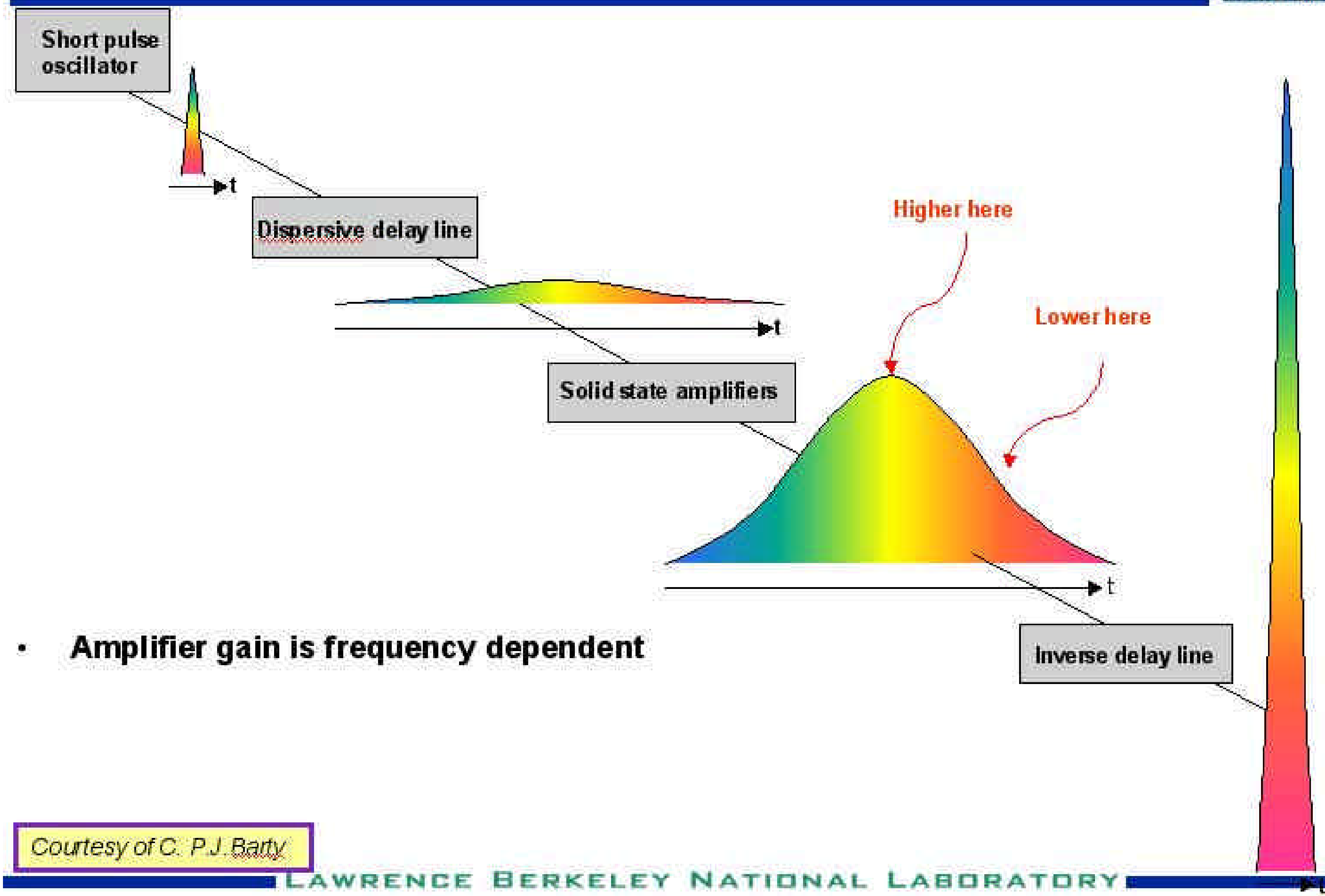
Exact dispersion can be calculated and preset before amplification



< 1-fs delay over 100 nm should allow ~12-fs amplification

Courtesy of C. P.J.Barty

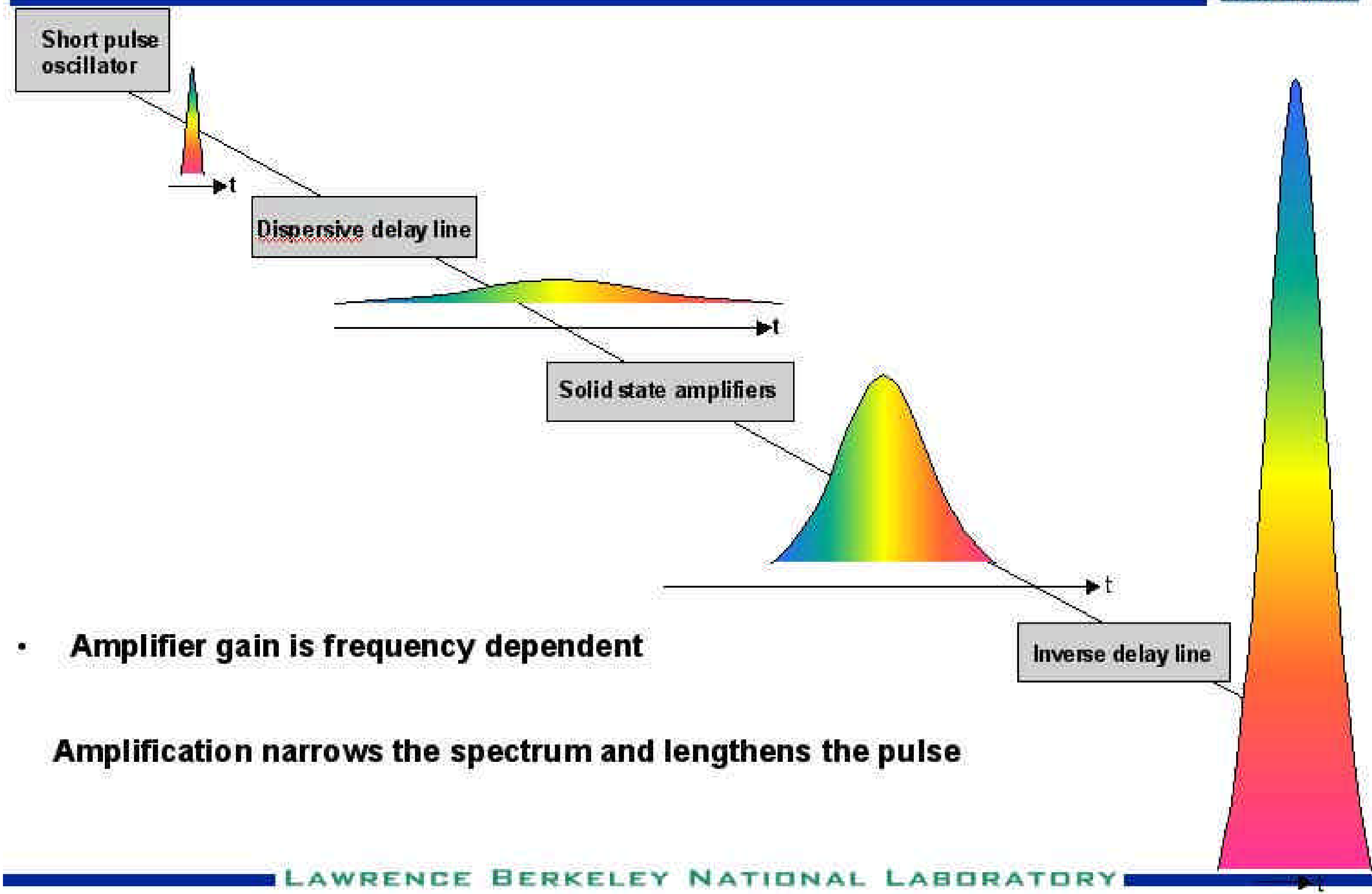
Gain Narrowing Lengthens Pulse



- **Amplifier gain is frequency dependent**

Courtesy of C. P.J. Barty

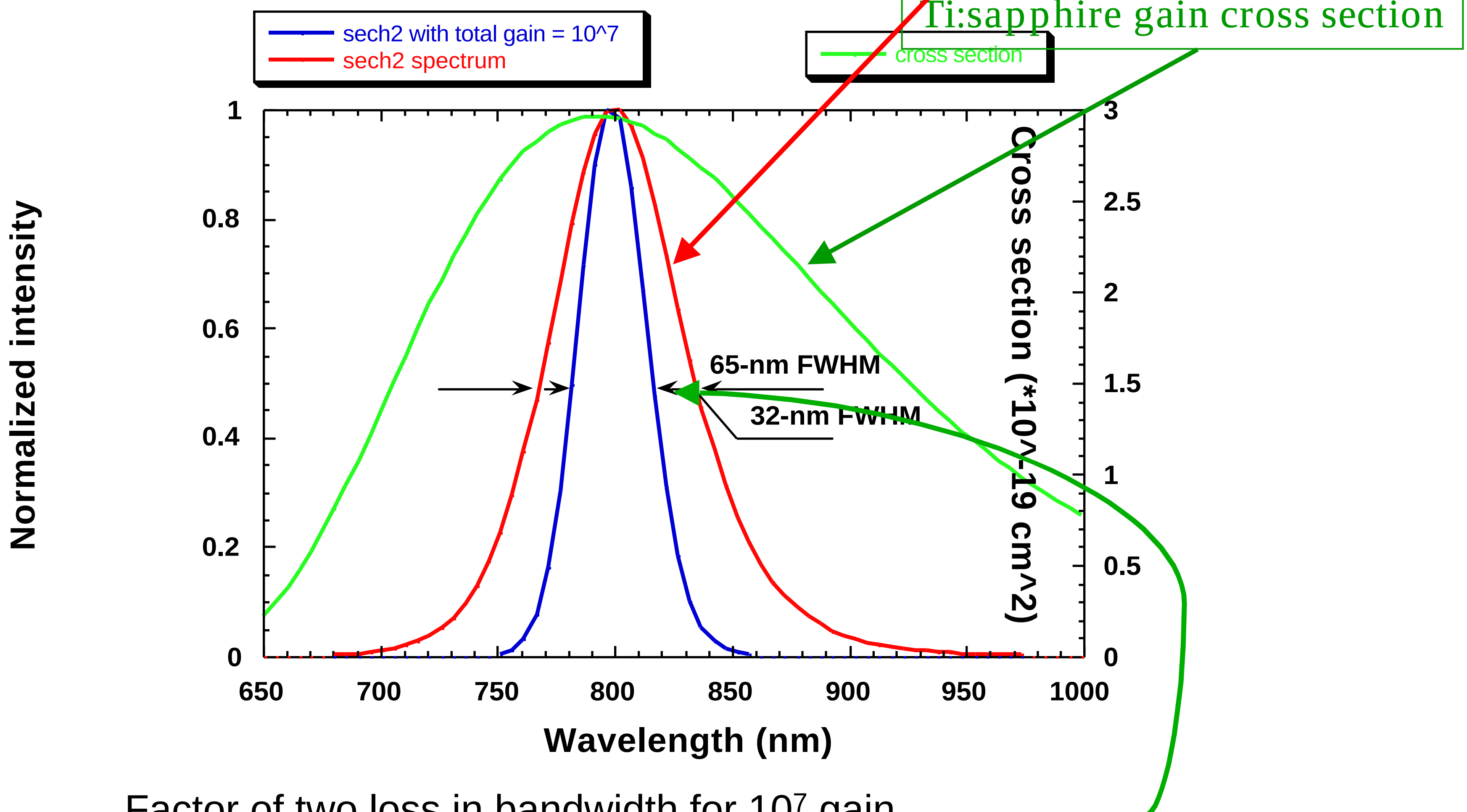
Gain Narrowing Lengthens Pulse



- Amplifier gain is frequency dependent

Amplification narrows the spectrum and lengthens the pulse

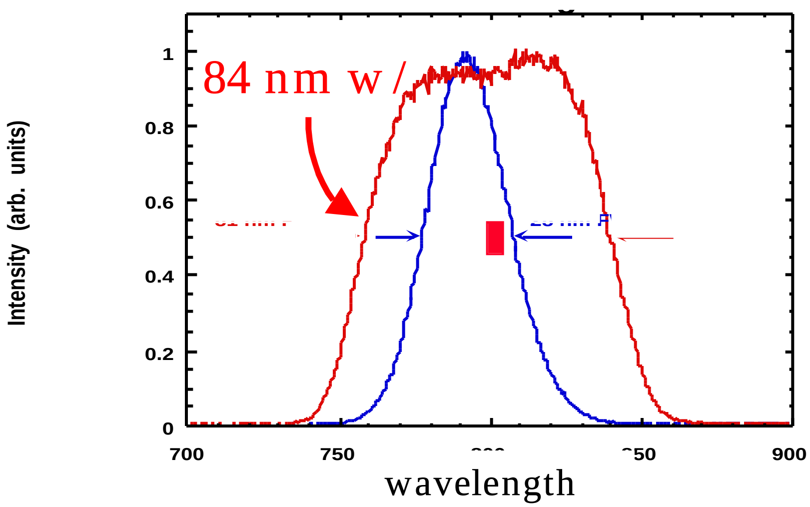
Gain Narrowing Example



Factor of two loss in bandwidth for 10^7 gain

Most terawatt systems have > 10^{12} small signal gain

Examples of Regenerative Pulse Shaping



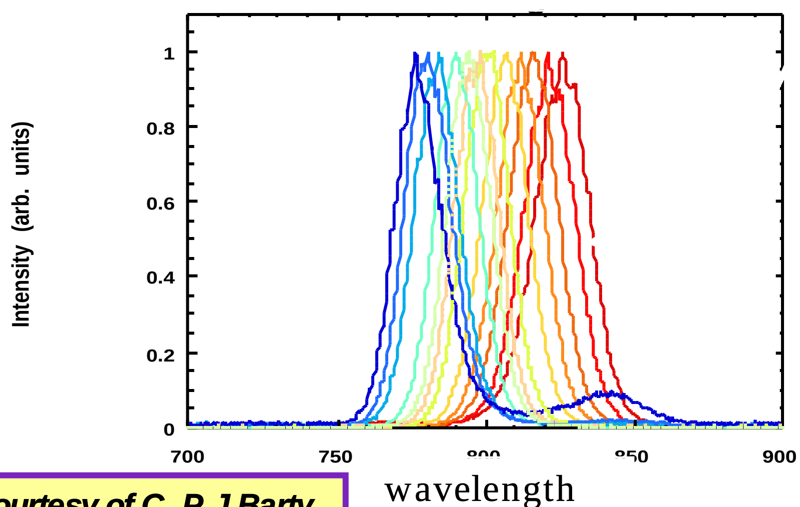
- **Beyond gain narrowing**
  —> 100 nm FWHM with 2 etalons

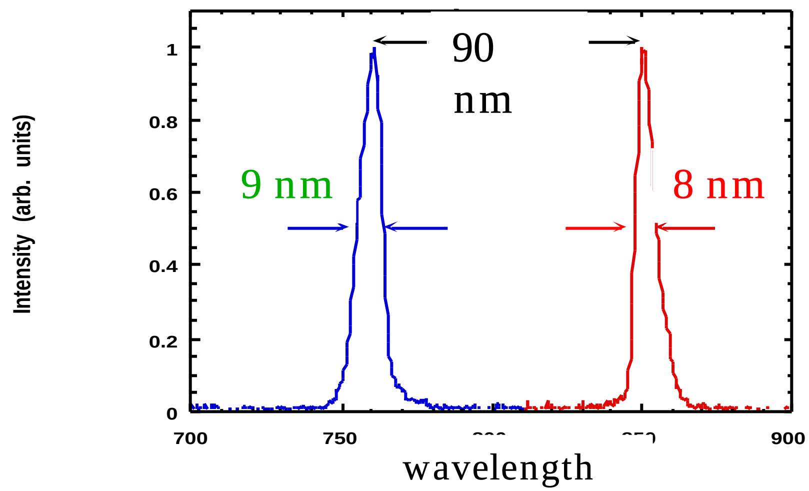
❍Electronic tuning

Piezo-controlled etalon

❍2 color amplification

Output is co-temporal and co-spatial
Beat wave acceleration
Difference frequency mixing





Courtesy of C. P.J.Barty

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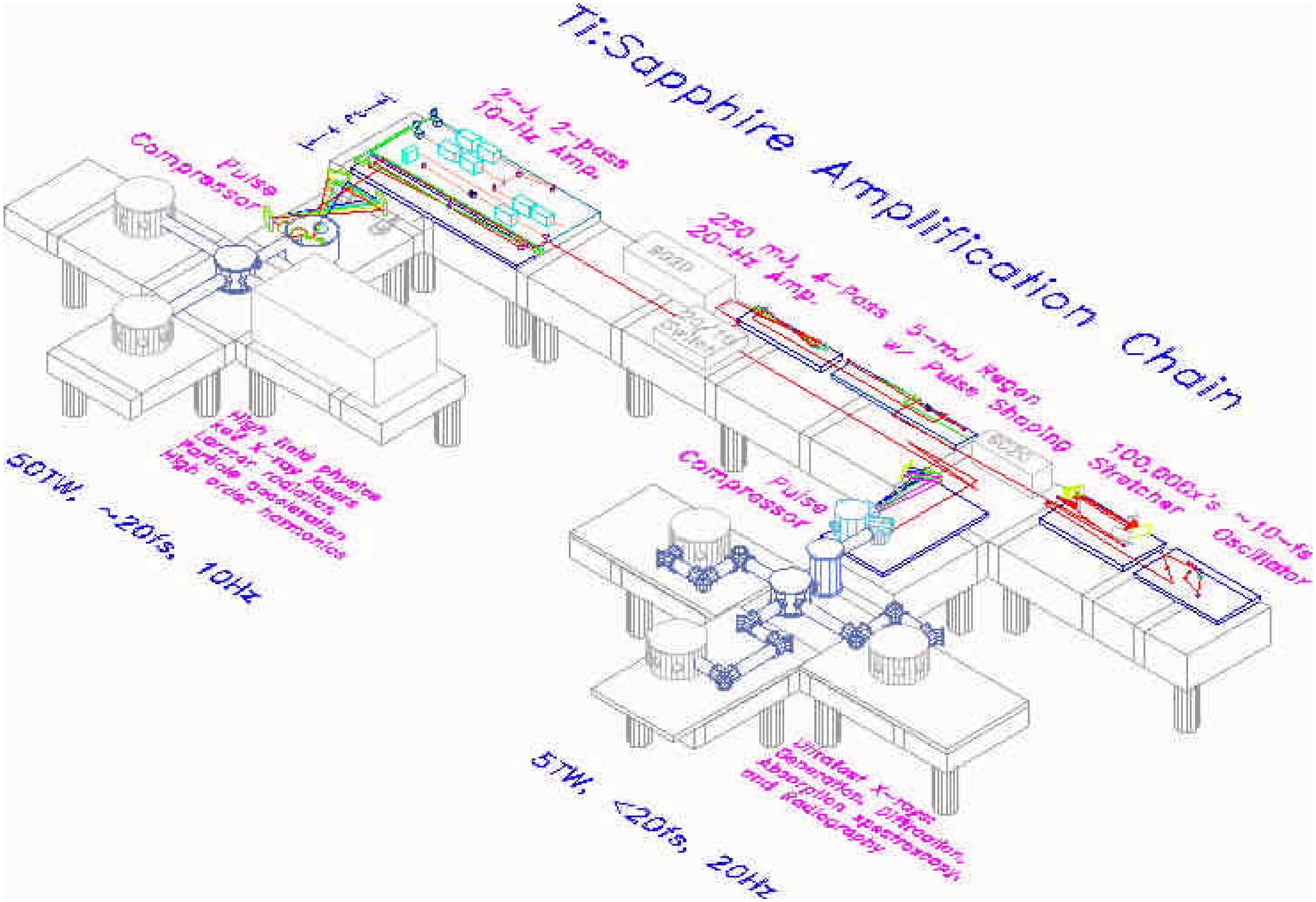
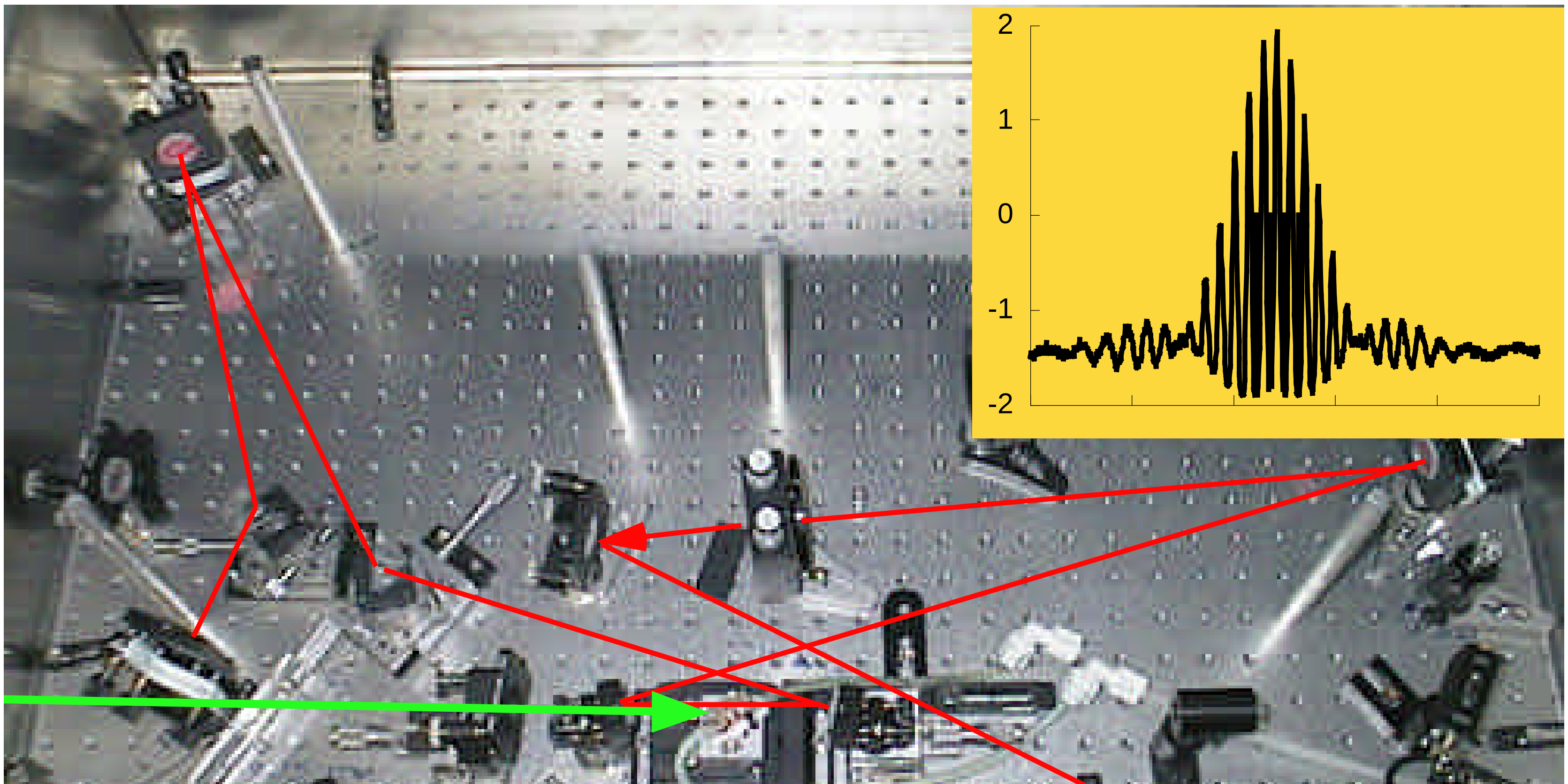
Case study #1
60 TW CPA laser system @ UCSD '97-'99



Walker, Tóth, et al., Optics Express 5, 196, (1999);
(http://www.opticsexpress.org/opticsexpress/tocv5n10.htm)

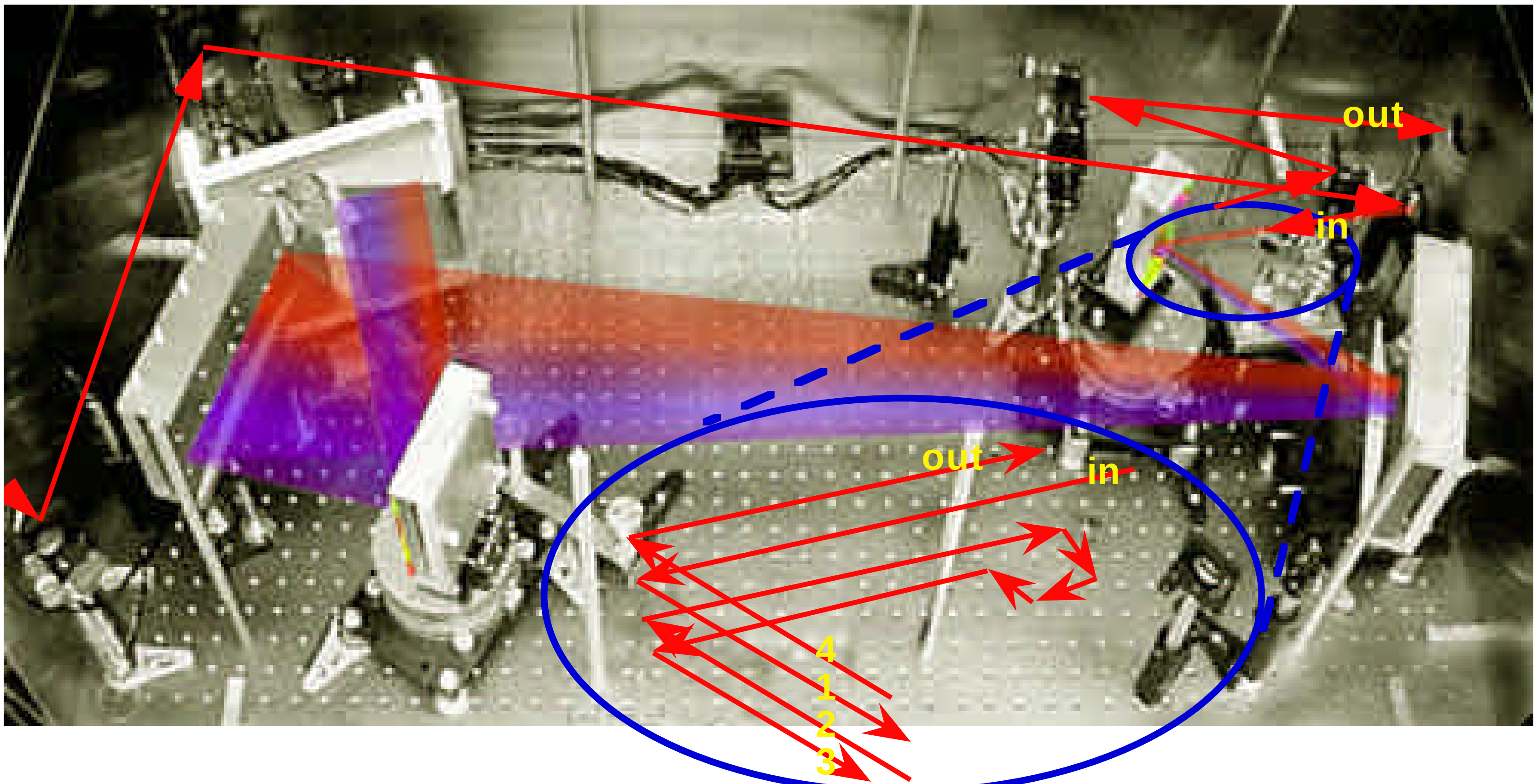
Master oscillator

University of California
San Diego



Oscillator 2 nJ, 15 fs → Stretcher 2 nJ, 800 ps → Preamplifiers 3 mJ / 280 mJ → Power amplifier 2.6 J, 800 ps → Compressor 1.3 J, 22 fs →

‘Aberration-full’ stretcher



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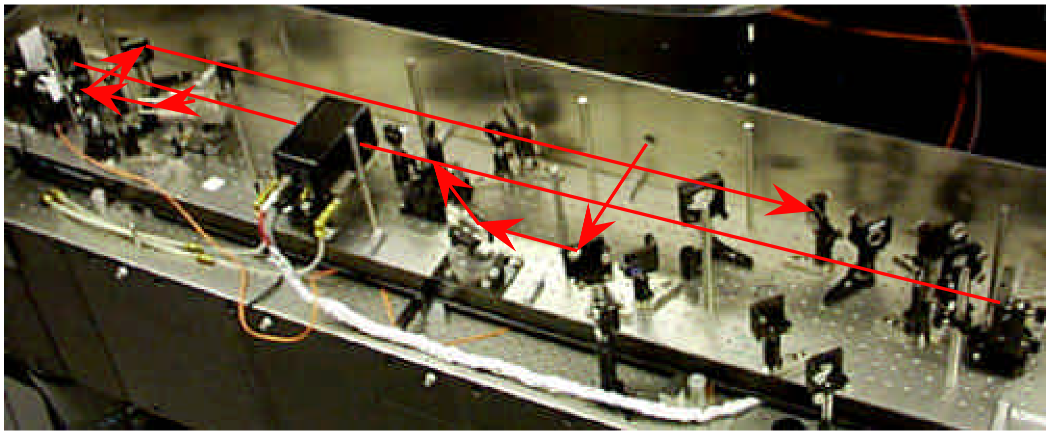
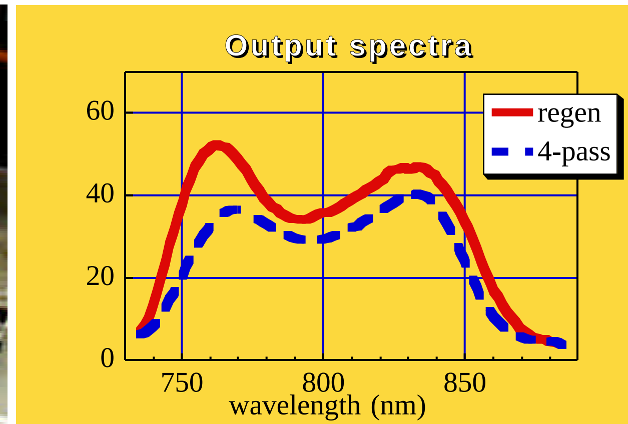
Regenerative and 4-pass amplifiers

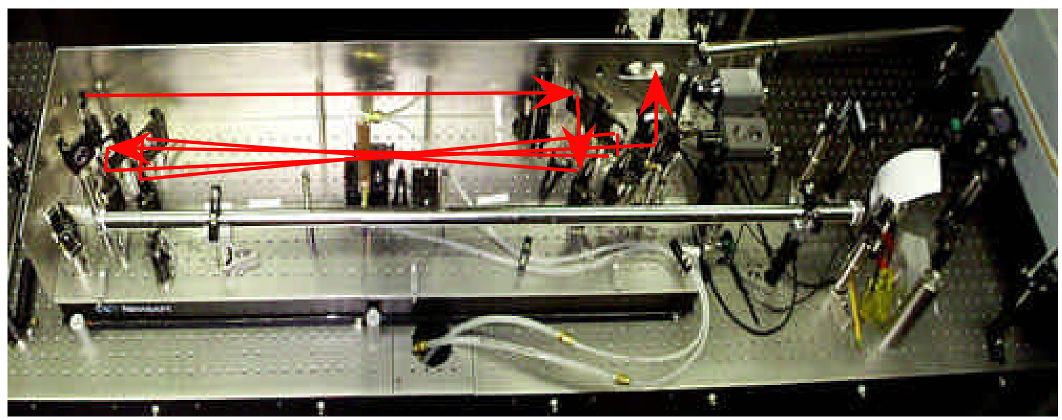
University of California San Diego





regenerative amplifier

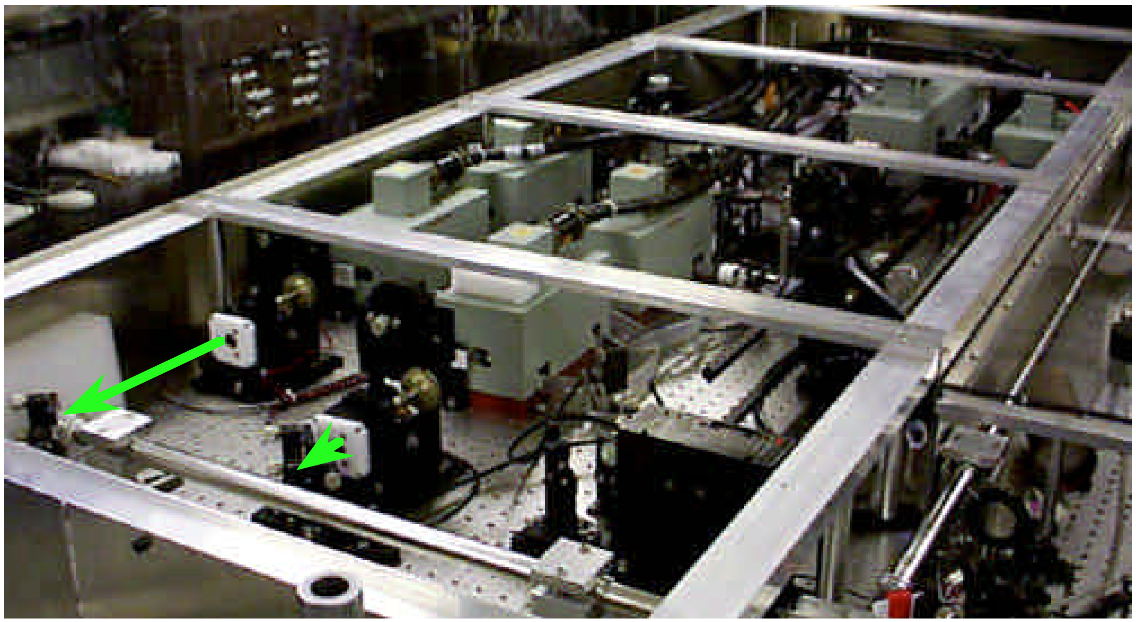
4-pass amplifier

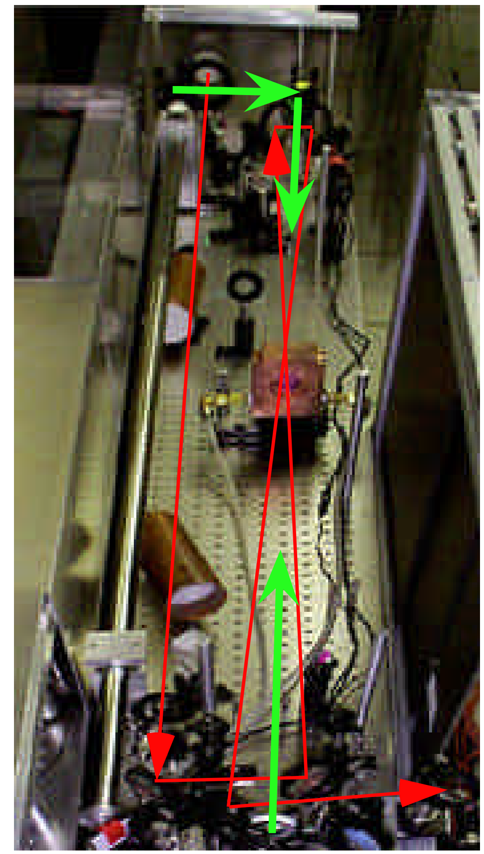


Oscillator	Stretcher	Preamplifiers	Power amplifier	Compressor
2 nJ, 15 fs	2 nJ, 800 ps	3 mJ / 280 mJ	2.6 J, 800 ps	1.3 J, 22 fs

2-pass final amplifier

University of California San Diego



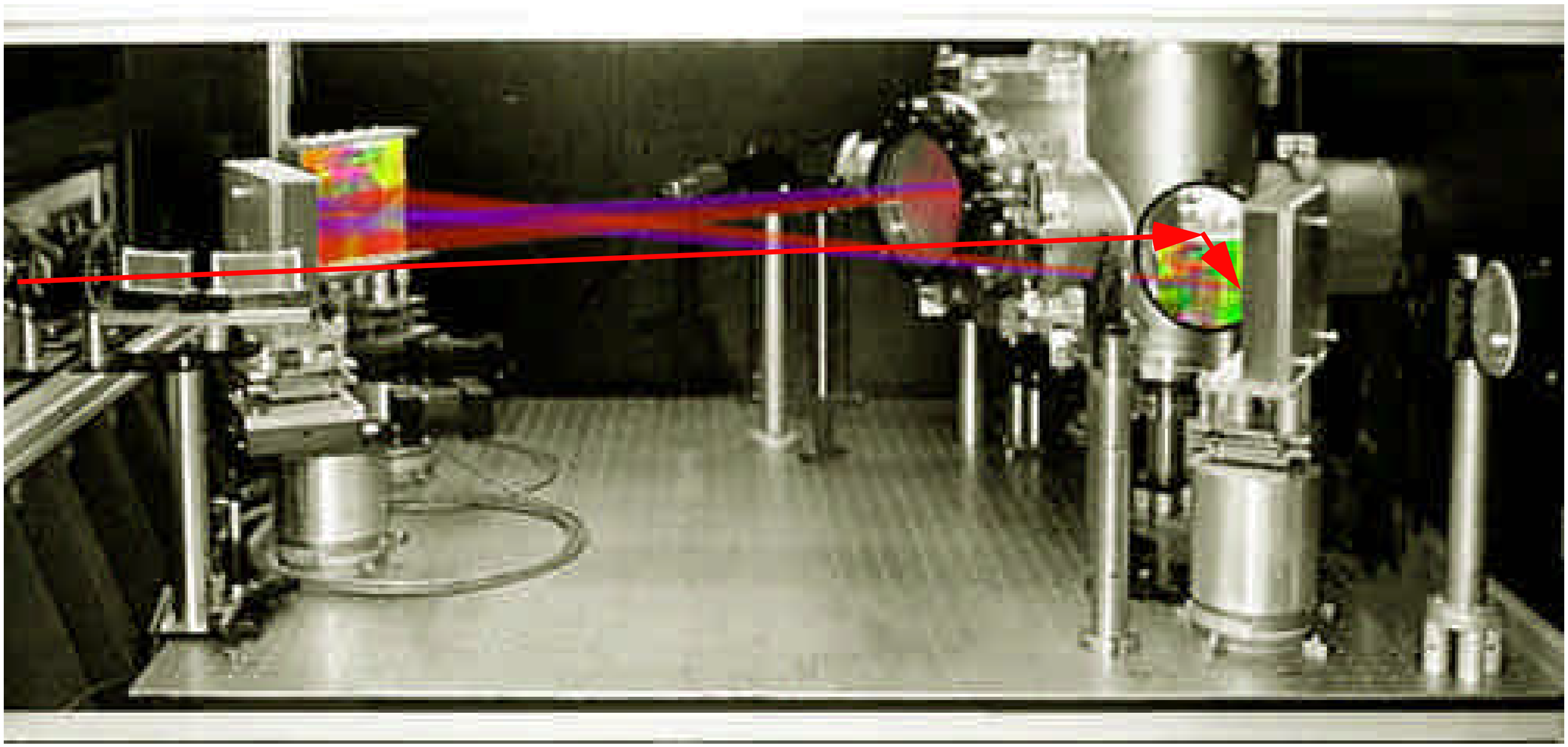


Nd:YAG pump laser

2-pass amplifier

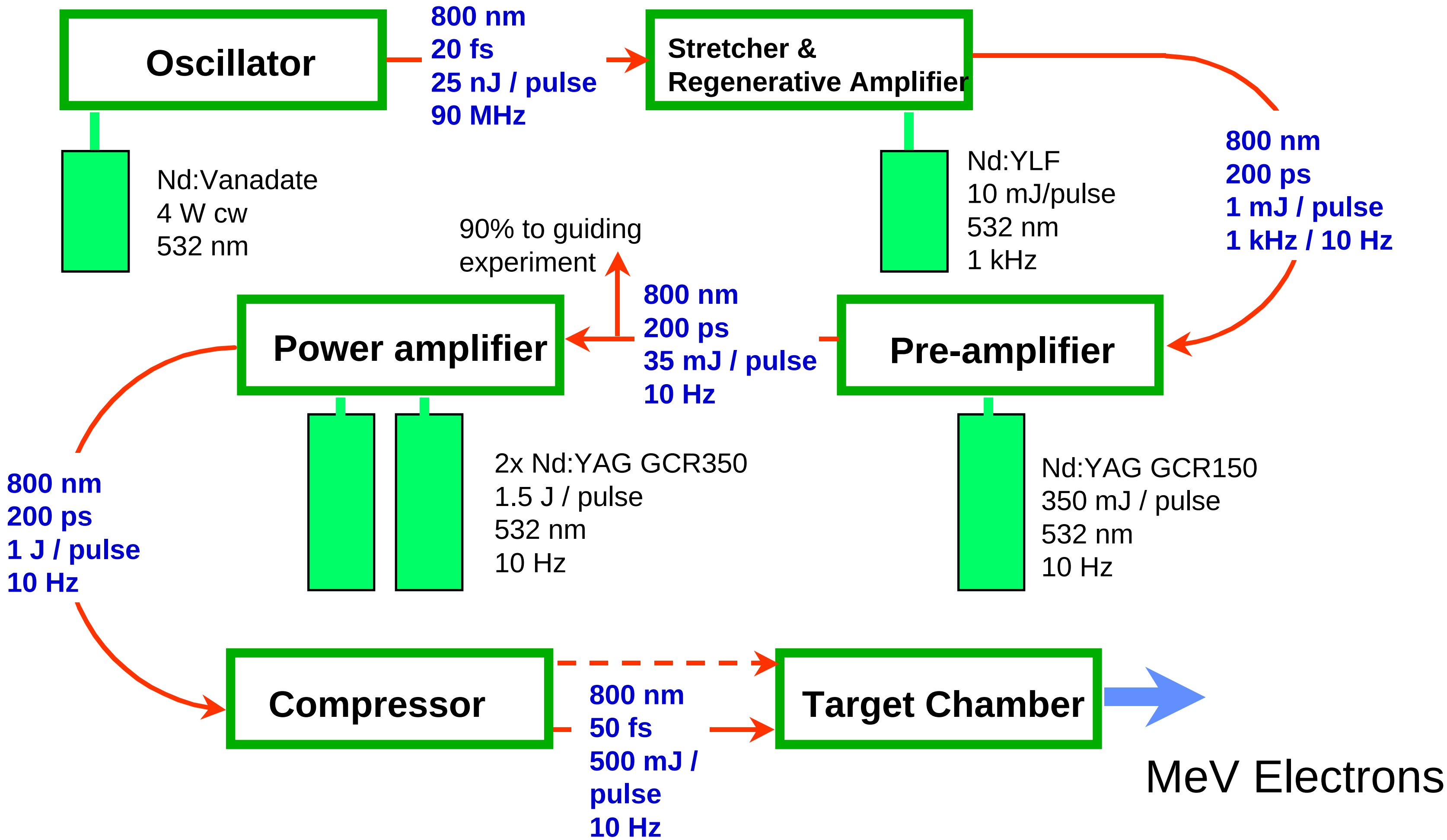
Oscillator	Stretcher	Preamplifiers	Power amplifier	Compressor
2 nJ, 15 fs	2 nJ, 800 ps	3 mJ / 280 mJ	2.6 J, 800 ps	1.3 J, 22 fs

Hybrid vacuum/air compressor

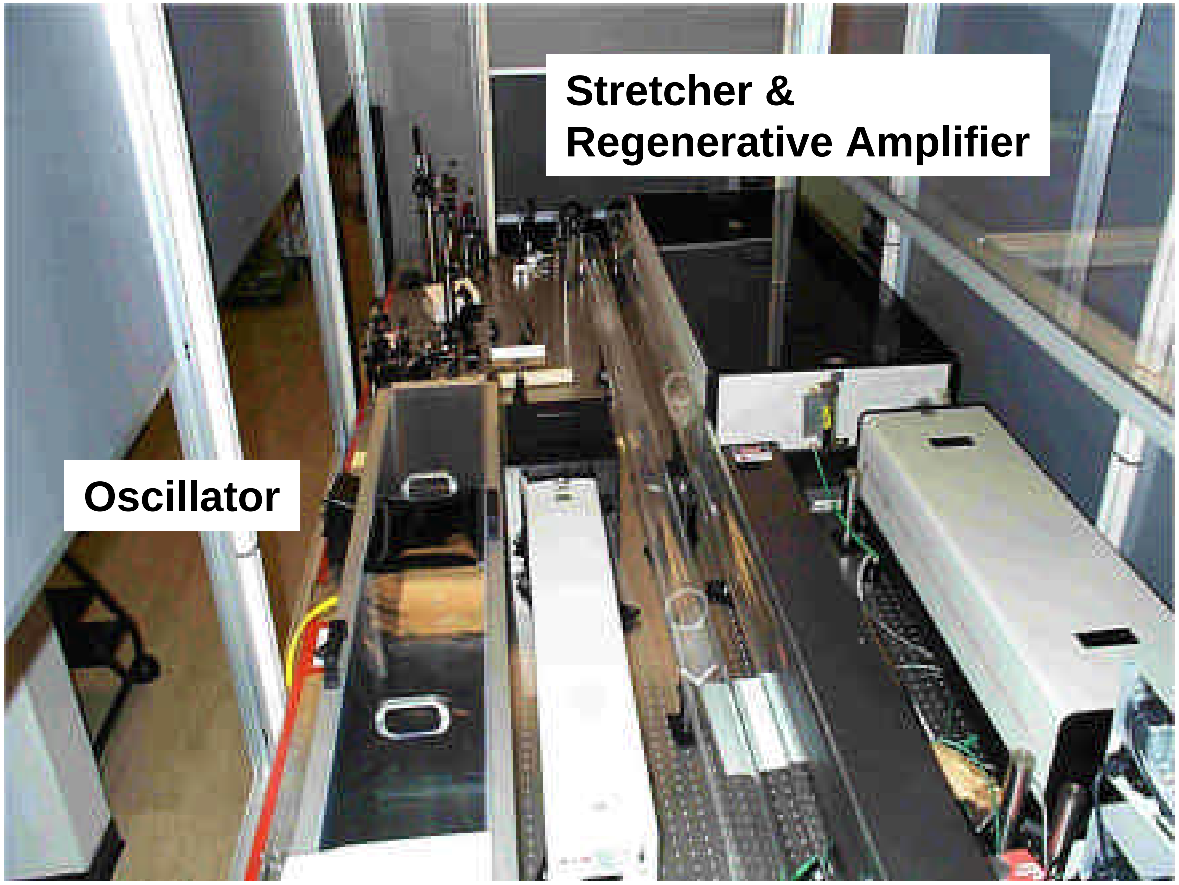


Oscillator 2 nJ, 15 fs → Stretcher 2 nJ, 800 ps → Preamplifiers 3 mJ / 280 mJ → Power amplifier 2.6 J, 800 ps → **Compressor 1.3 J, 22 fs** →

Case study #2
10 TW CPA laser system @ LBNL



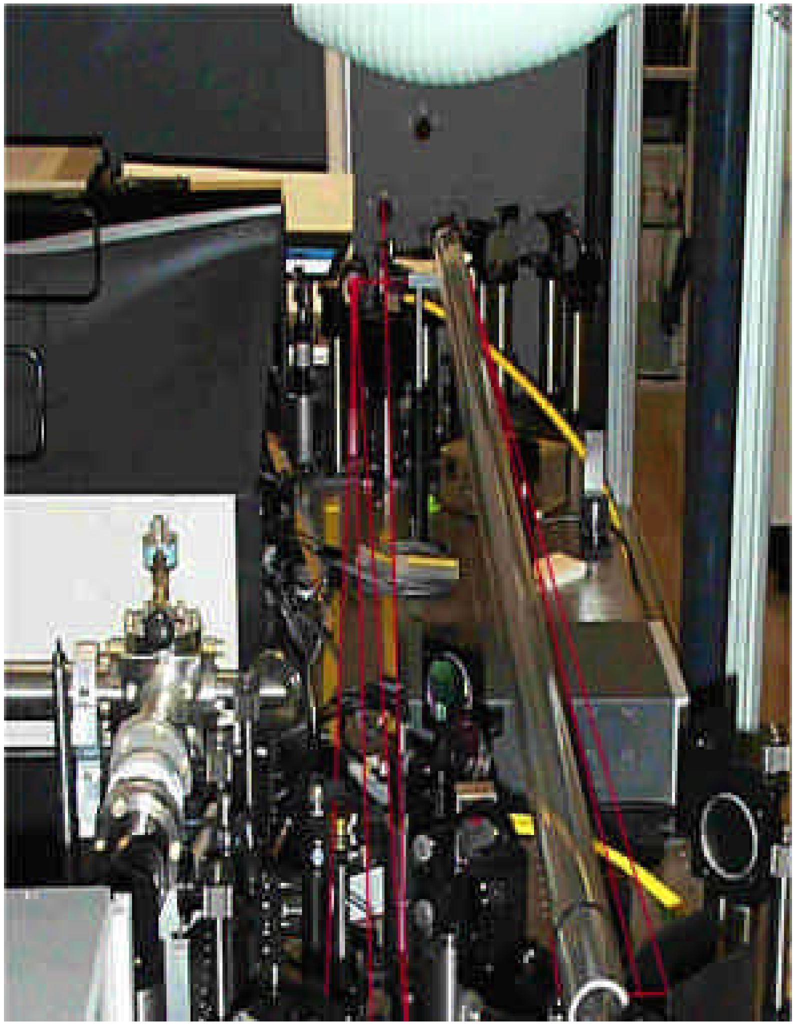
Oscillator and Stretcher/Regenerator



Oscillator:
Rep rate: 90 MHz
Pulse energy: 3 nJ
Pulse length: 20 fs

Stretcher/Regenerator:
Rep rate: 1 kHz / 10Hz
Pulse energy: 1 mJ
Pulse length: 200 ps

Pre-amplifier



3-pass Ti:Al_2O_3 amplifier pumped by frequency doubled Nd:YAG (GCR150) 350 mJ / pulse

In:

Pulse energy: 1 mJ

Out:

Pulse energy: 35 mJ

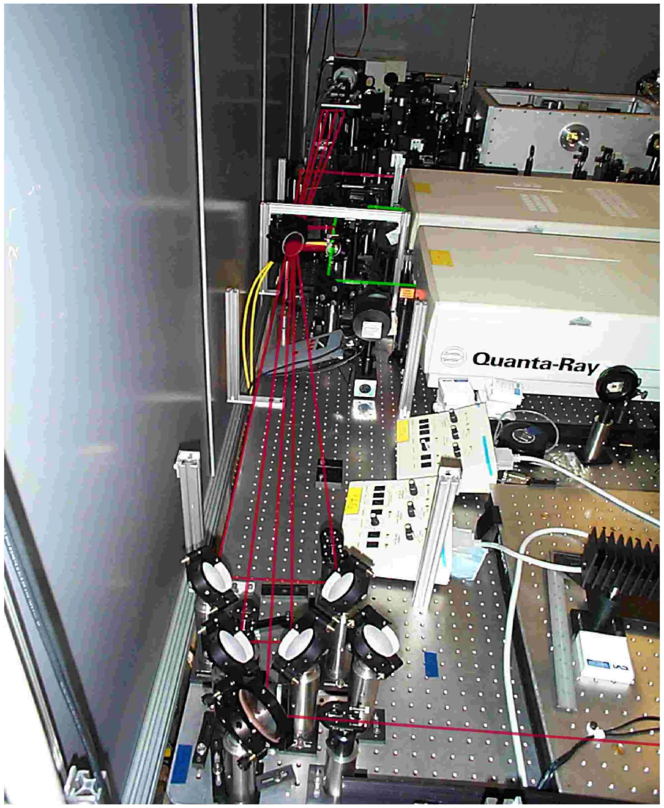
- 90% to guiding experiment
- 10% to colliding pulse experiment

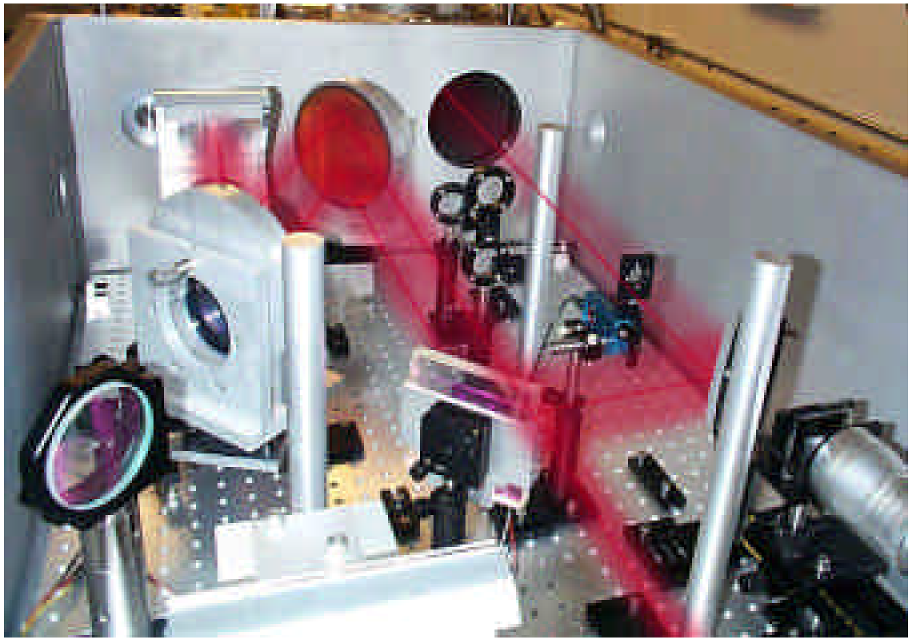
Rep Rate: 10 Hz

Pulse length: 200 ps

Wavelength: 800 nm

Power amplifier/compressor





Rep Rate: 10 Hz
Pulse length: 200 ps
Wavelength: 800 nm
E_{in}= 3 mJ ⇒ E_{out}= 1 J

Pulse energy: 500 mJ
Pulse length: < 50 fs
⇒ Power > 10 TW

Outline

- Needs ⇔ Capabilities
- Lasers — 102
- Amplification principles
  - — Chirped Pulse Amplification (CPA)
- Case studies
  - — multi-TW CPA systems @ LBNL, ex-UCSD
- Beam diagnostic tools
- Lasers around the globe
- Special acceleration related issues, future

Diagnostic tools - for lasers, plasmas & beams

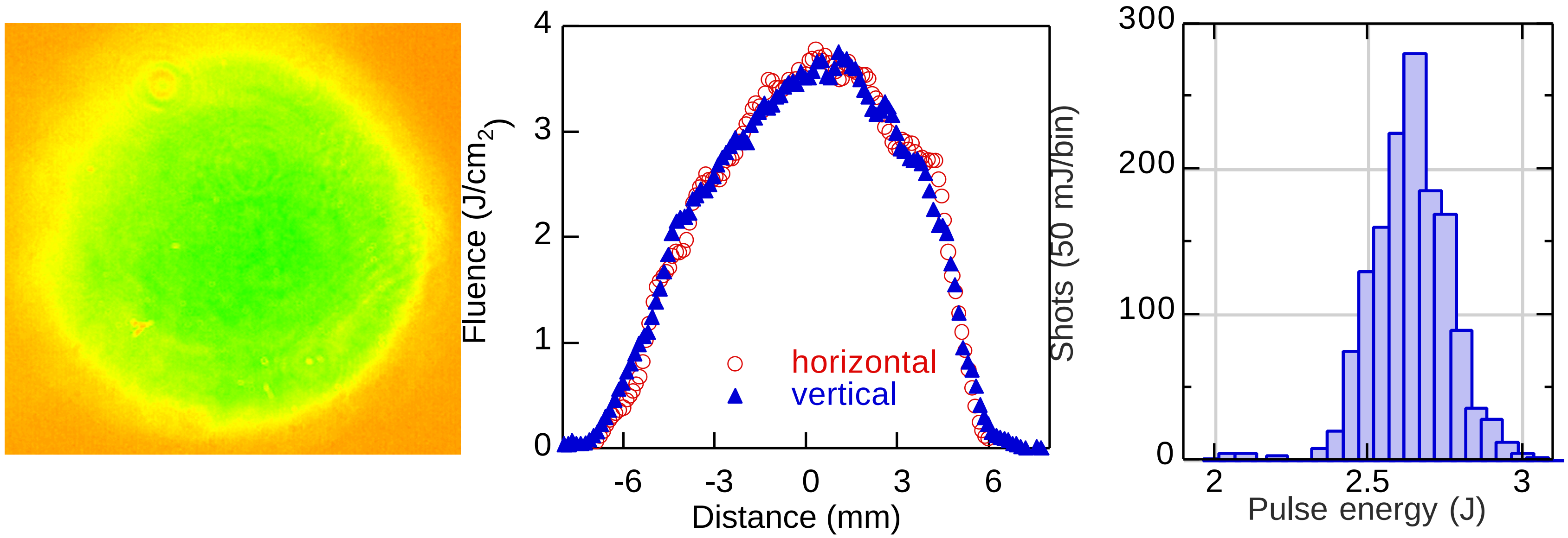
- Energy, contrast
  — power meters, diodes, calibrated attenuators
- Spot size, divergence
  — cameras, M^2 method
- Pulse duration, phase and amplitude
  — Autocorrelation, FROG, SPIDER
  Frequency Resolved Optical Gating,
  Spectral-Phase Interferometry for Direct Electric field Reconstruction

- Plasma diagnostics
  — side- and on-axis interferometry, spectroscopy
- Particle beam diagnostics
  — OTR, Thomson scattering, etc.

⇒ P. Catravas - Workgroup T9

Optical diagnostics —
Beam profile and fluctuation

University of California San Diego



(a) (b) (c)

M^2 Measurement strategy

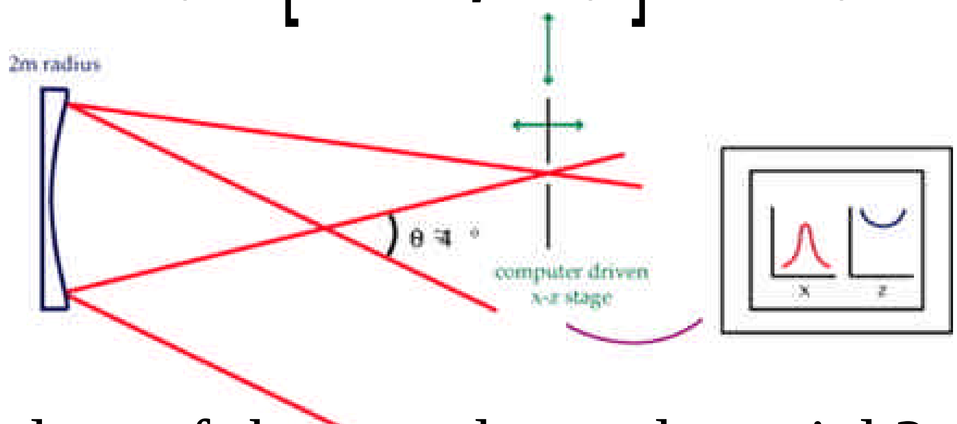
Focus with long focal length mirror

Measure transverse profile vs. z

Calculate second moment of each profile: $W(z) \equiv \sigma^{(2)}(z)$

Compare to Gaussian with the same far field

$$W^2(z) = W_0^2 + \left[\mathbf{M}^2 (\lambda / \pi W_0)\right]^2 (z - z_0)^2$$

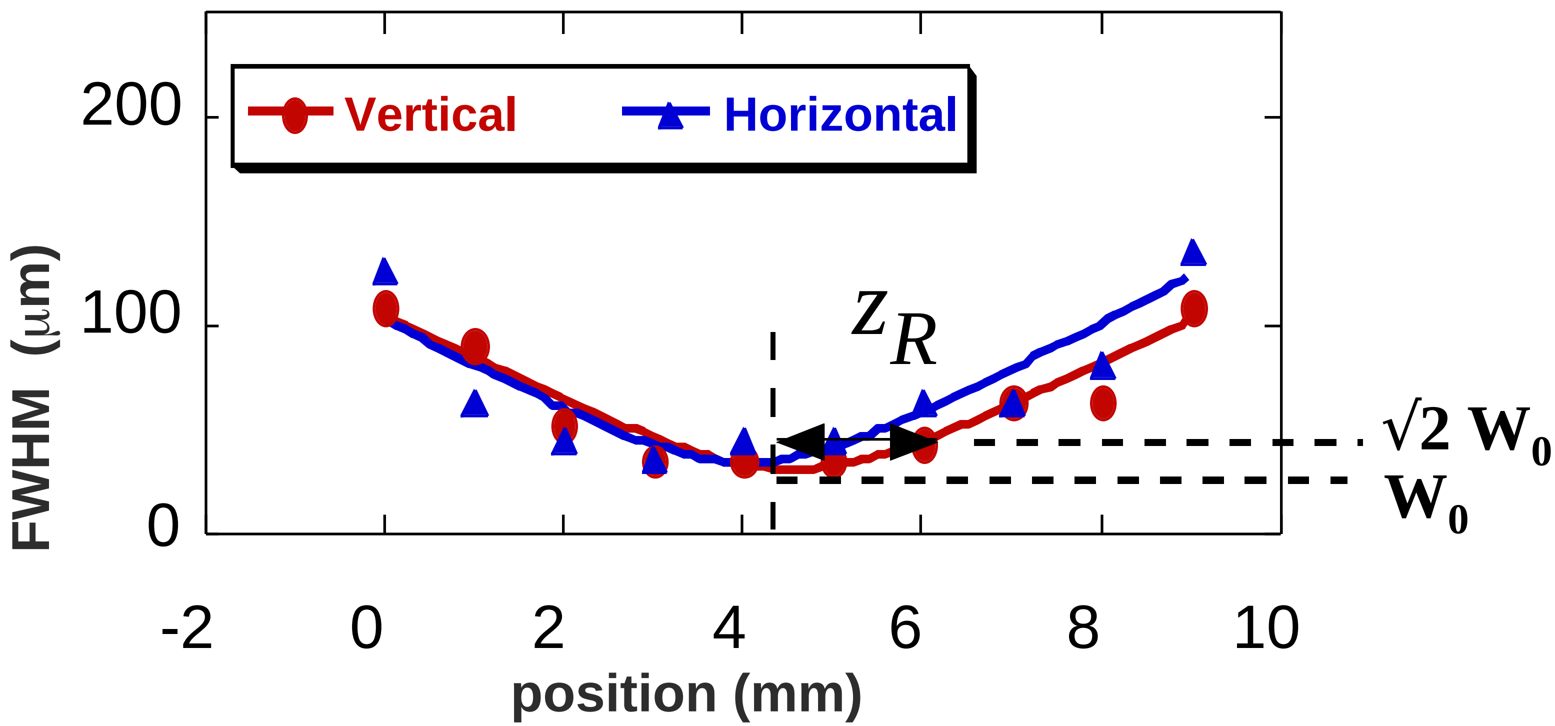


The product of the angular and spatial 2nd moments is M^2 x's that of a Gaussian beam, i.e. M^2 x's the minimum

M^2 Beam Quality Measurement

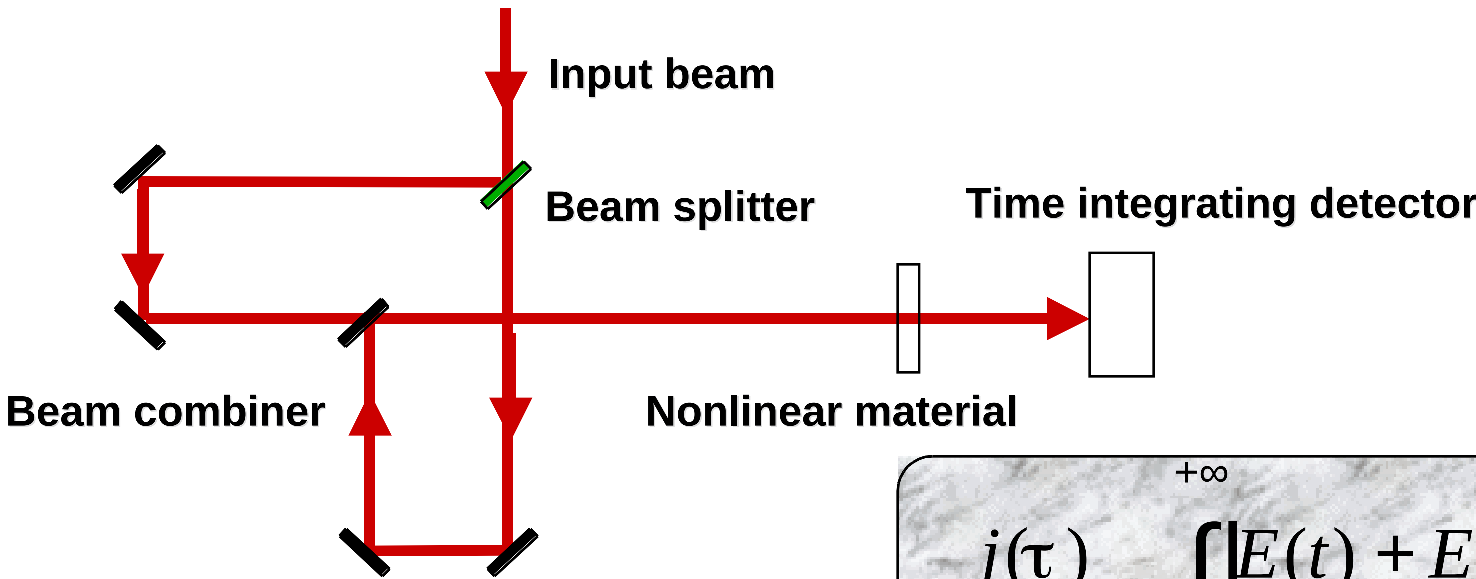
$$W^2(z) = W_0^2 + \left[\mathbf{M}^2 (\lambda / \pi W_0)\right]^2 (z - z_0)^2$$

$$z_R = \pi W_0^2 / \mathbf{M}^2 \lambda$$



Siegman, SPIE Proc. ***1224****, pp.2-14 1990*

Diagnostics – Autocorrelation



$$j(\tau) \quad \int_{-\infty}^{+\infty} \left| E(t) + E(t-\tau) \right|^2 dt$$

- **Classes:**
  - **collinear**
  - **non-collinear (background free)**
  - **single-shot (by mapping delay to space)**
  - **fringe-resolved (interferometric)**
  - **higher-order (better contrast)**
  - **wavelength specificity (by choice of nonlinear material)**

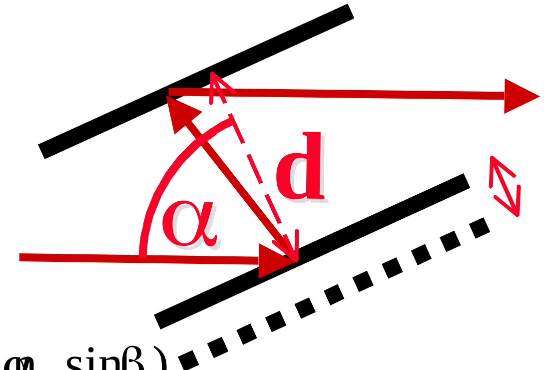
Higher order phases – Definitions

$$\varphi(\omega) = \varphi_0 + \left.\frac{\partial\varphi}{\partial\omega}\right|_{\omega_0}(\omega-\omega_0) + \frac{1}{2}\left.\frac{\partial^2\varphi}{\partial\omega^2}\right|_{\omega_0}(\omega-\omega_0)^2 + \frac{1}{3}\left.\frac{\partial^3\varphi}{\partial\omega^3}\right|_{\omega_0}(\omega-\omega_0)^3 + \frac{1}{4}\left.\frac{\partial^4\varphi}{\partial\omega^4}\right|_{\omega_0} + \ldots$$

time delay **'GDD'** **'cubic'** **'quartic'**

- In real materials they are strongly interrelated
- Independent control of them usually not possible
- Higher orders mostly sensitive to the spectral wings

Higher order phases – Example of grating pair



- General:

$$\left.\frac{\partial^2\varphi}{\partial\omega^2}\right|_{\omega_0} = \text{GDD} = -d\,\frac{N^2\lambda^3}{2\pi c^2}\,\frac{1}{\cos^3(\beta)}$$

$$\left.\frac{\partial^3\varphi}{\partial\omega^3}\right|_{\omega_0} = \text{'cubic'} = 3d\,\frac{N^2\lambda^4}{4\pi^2 c^3}\,\frac{(1+\sin\alpha\ \sin\beta)}{\cos^5\beta} = -\frac{3\lambda}{2\pi c}\,\frac{(1+\sin\alpha\ \sin\beta)}{\cos^2\beta}\,(\text{GDD})$$

$$\left.\frac{\partial^4\varphi}{\partial\omega^4}\right|_{\omega_0} = \text{'quartic'} = \frac{3\lambda^2}{4\pi^2 c^2}\,\frac{[\cos^2\alpha\ \cos^2\beta - 5(1+\sin\alpha\ \sin\beta)^2]}{\cos^4\beta}\,(\text{GDD})$$

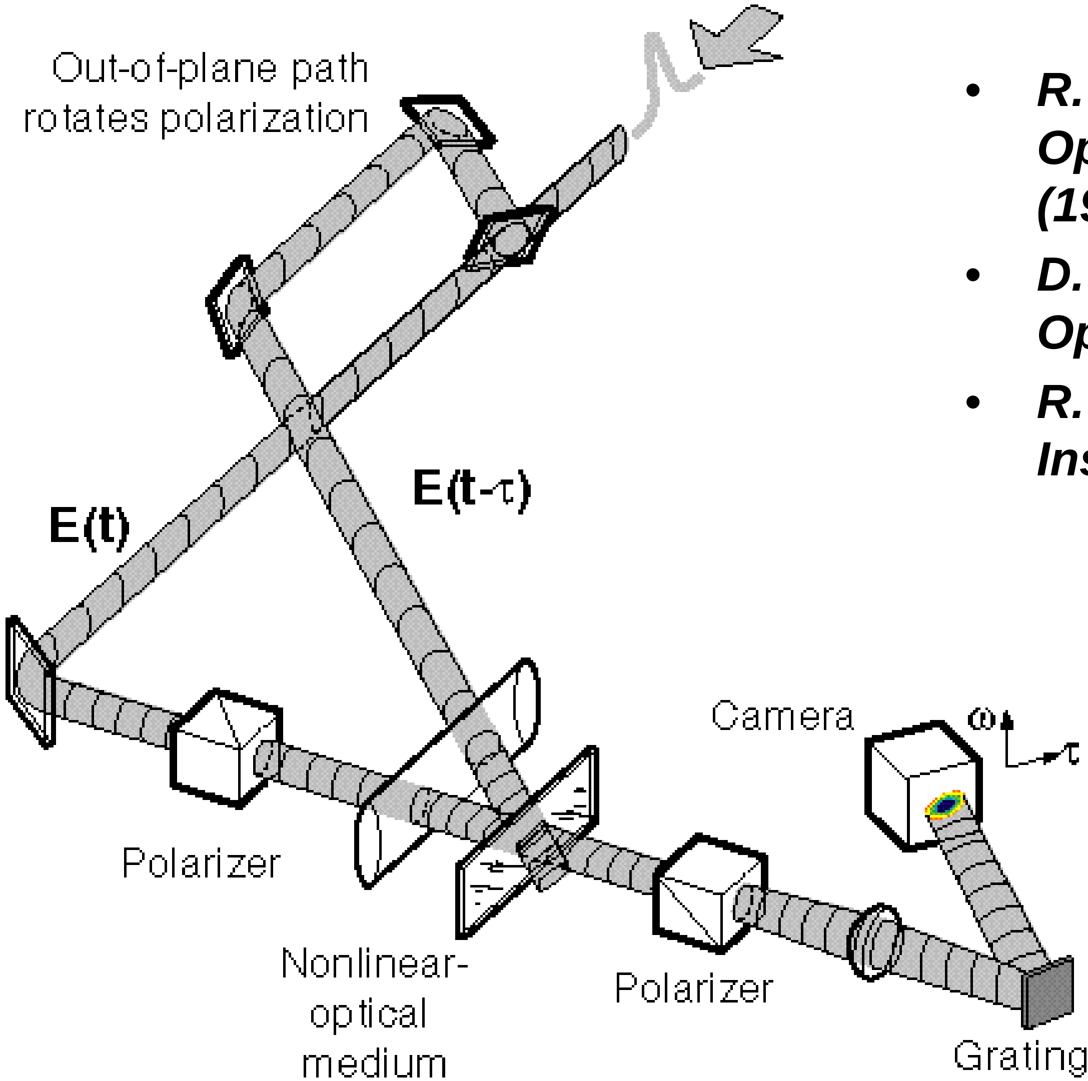
$$\text{'slope of GDD'} = \frac{\partial(\text{GDD})}{\partial \text{d}} = -\frac{N^2\lambda^3}{2\pi c^2}\,\frac{1}{\cos^3(\beta)}$$

$$\text{'slope of cubic phase'} = \frac{\partial(\text{cubic})}{\partial \text{d}} = 3\,\frac{N^2\lambda^4}{4\pi^2 c^3}\,\frac{(1+\sin\alpha\ \sin\beta)}{\cos^5\beta}$$

α = angle of incidence
β = angle of diffraction
d = grating separation
N = groove density

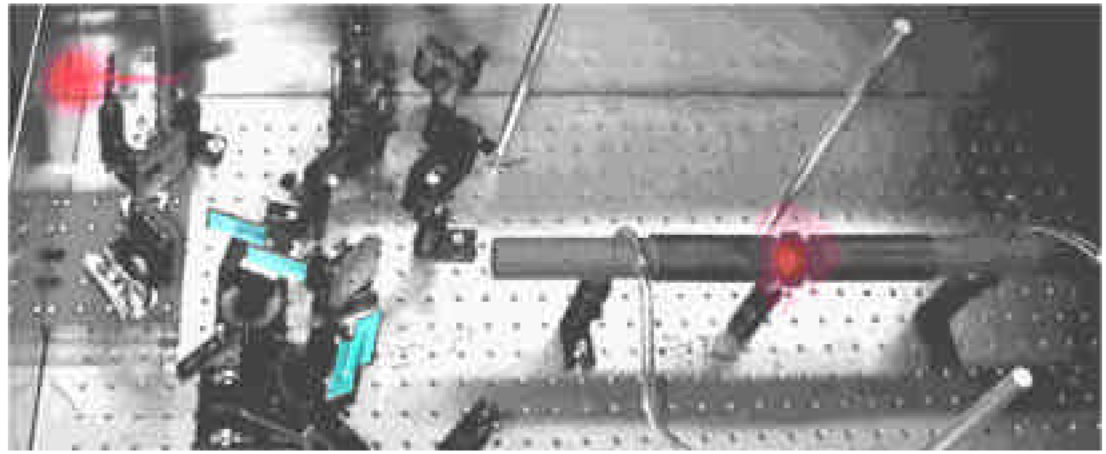
e.g. IEEE J. QE-30, 1662, (1994); RSI 69, 1207 (1998)

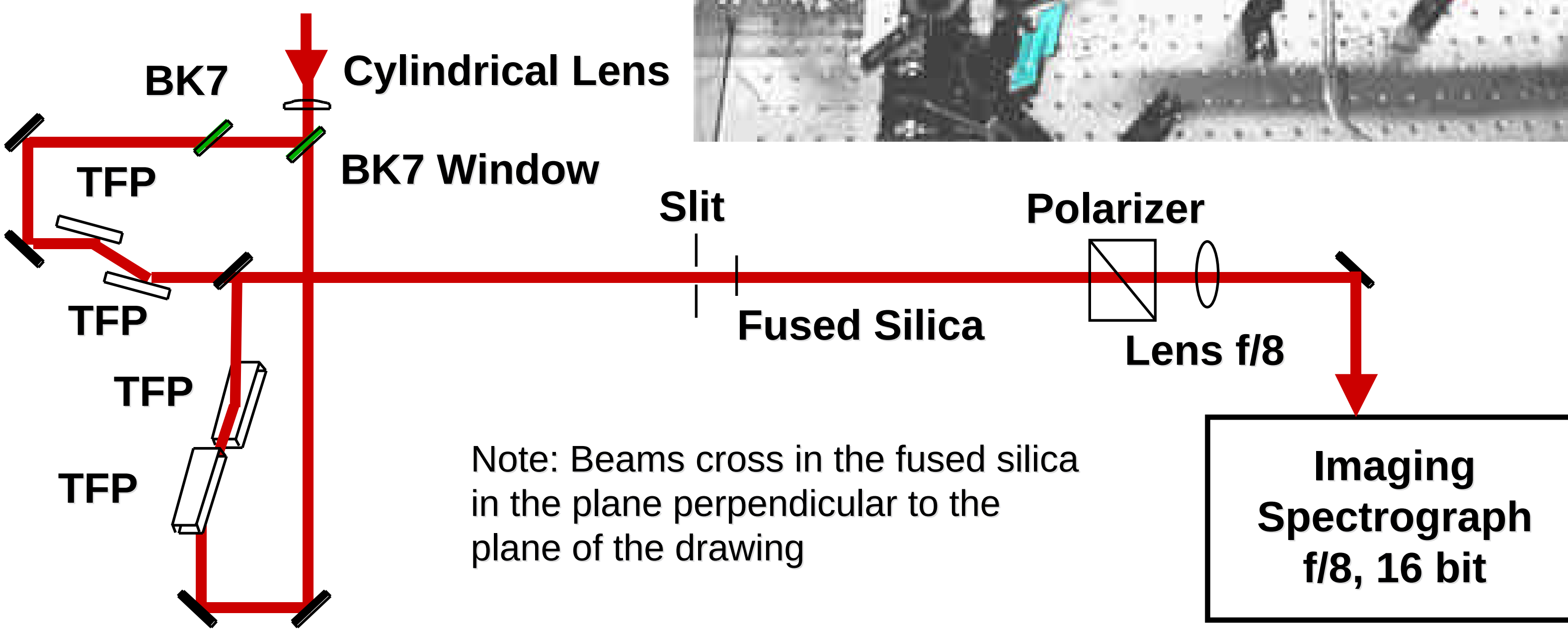
Diagnostics – Standard PG FROG



- ***R. Trebino and D. J. Kane, J. Opt. Soc. Amer. A 10, 1101 (1993).***
- ***D. J. Kane and R. Trebino, Opt. Lett. 18, 823 (1993).***
- ***R. Trebino, et al., Rev. Sci Instrum. 68, 3277 (1997).***

Diagnostics – Low-dispersion FROG

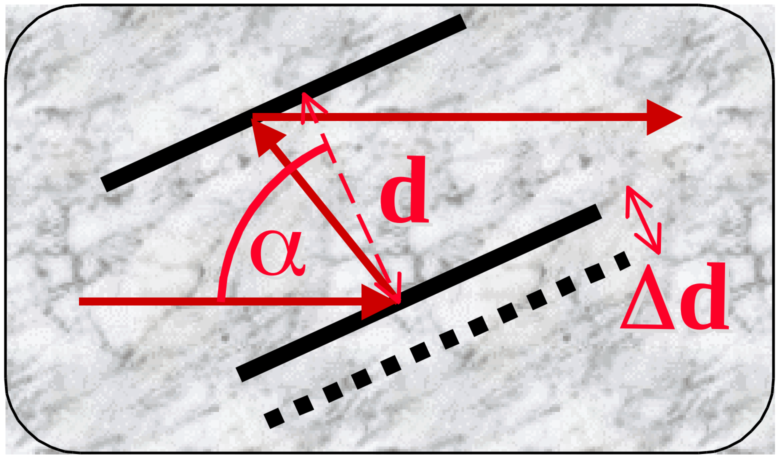




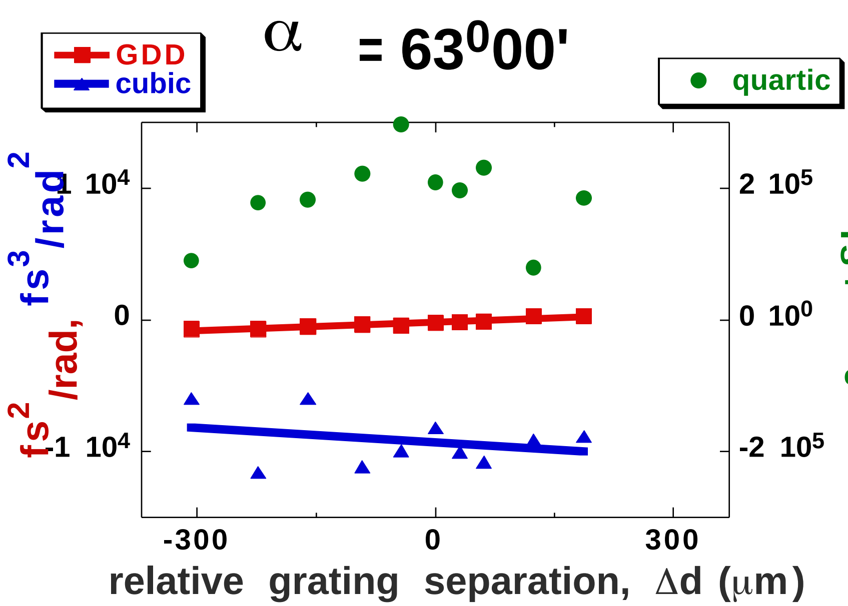
Note: Beams cross in the fused silica in the plane perpendicular to the plane of the drawing

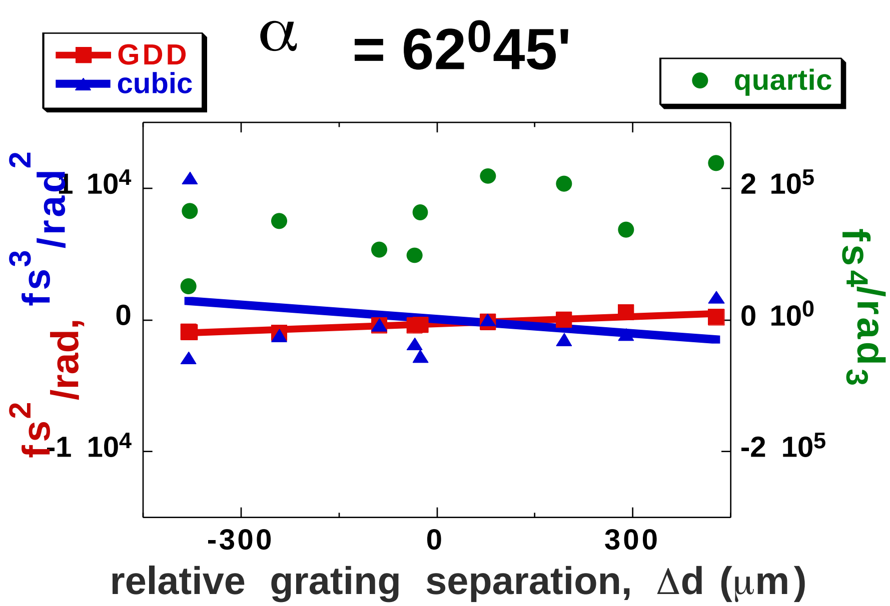
Fittinghoff et al, IEEE JSTQE-4, 430, (1998)
Tóth et al, Ultrafast Phenomena XI, 109, (1998)

Higher order phases



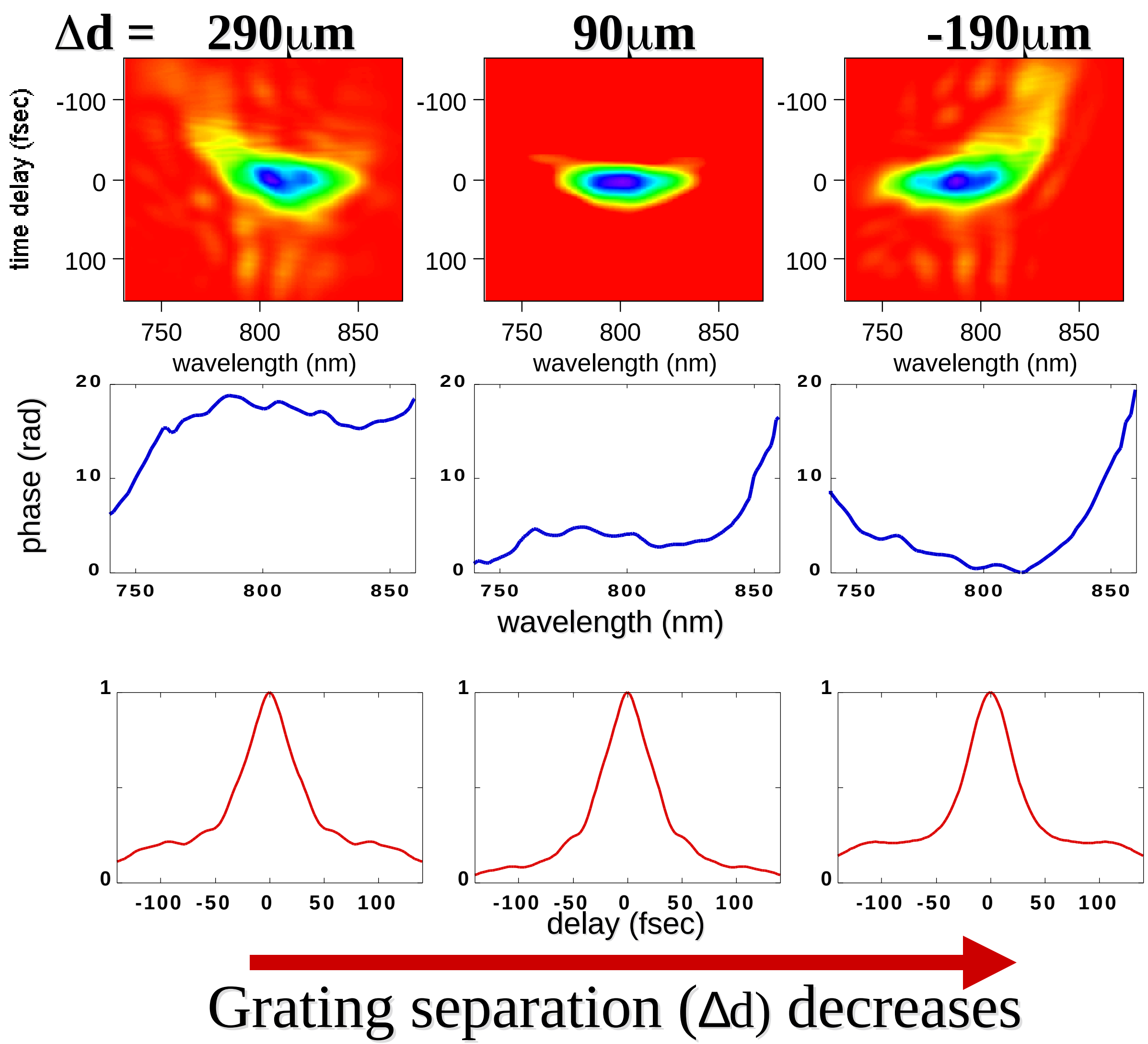
Optimization of the parameters of the grating compressor



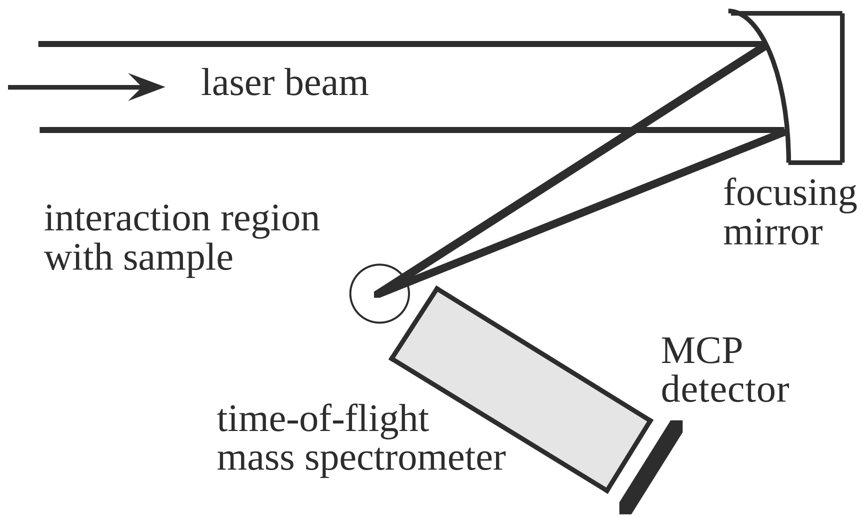


FROG vs. autocorrelation

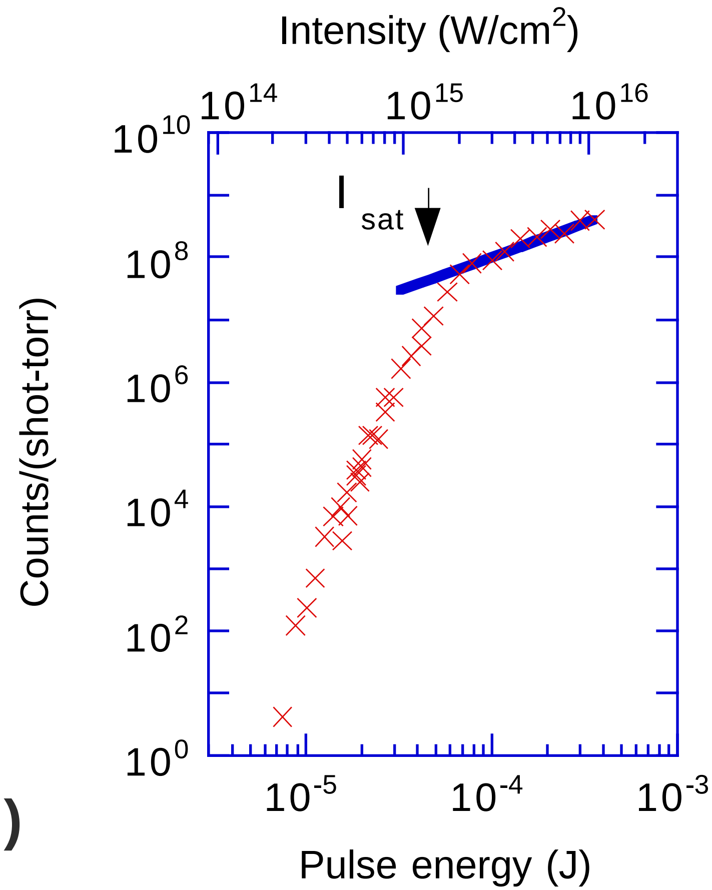
- **Intuitive images** ☺
- **Detailed phase characteristics** ☺
- **Autocorrelation** ☹



Focused peak intensity — Measured by Optical Field Ionization



(a)



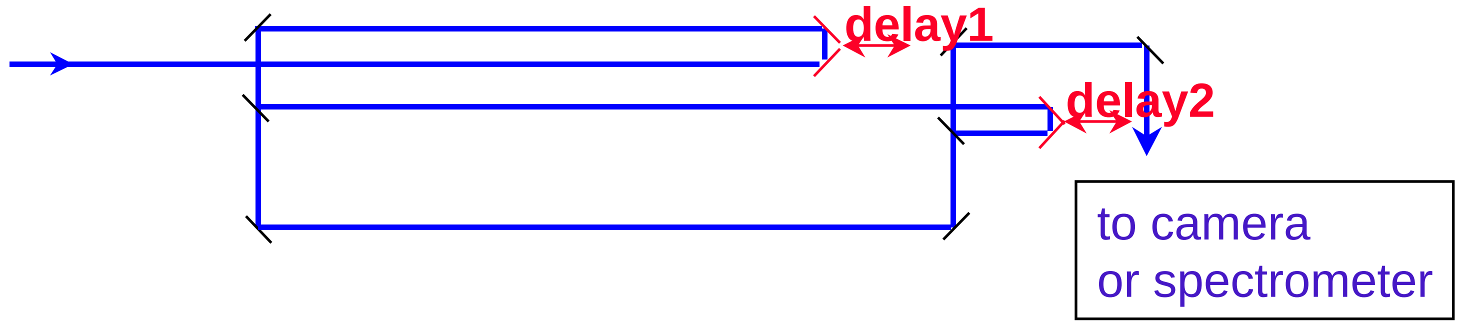
(b)

I_{peak} = 5.6 * 10^{19} W/cm^2

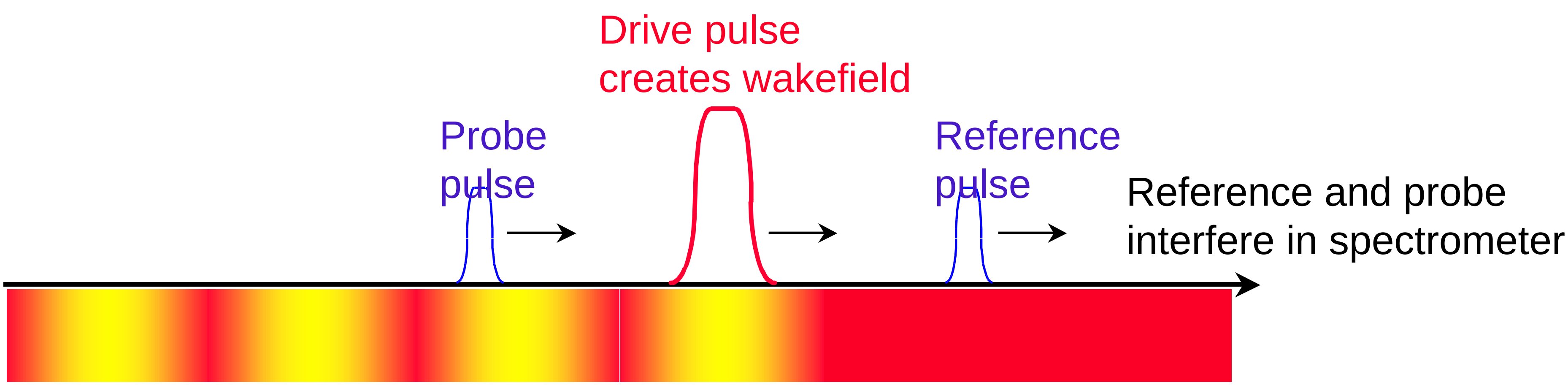
@ 1.3 J full energy

Longitudinal interferometry

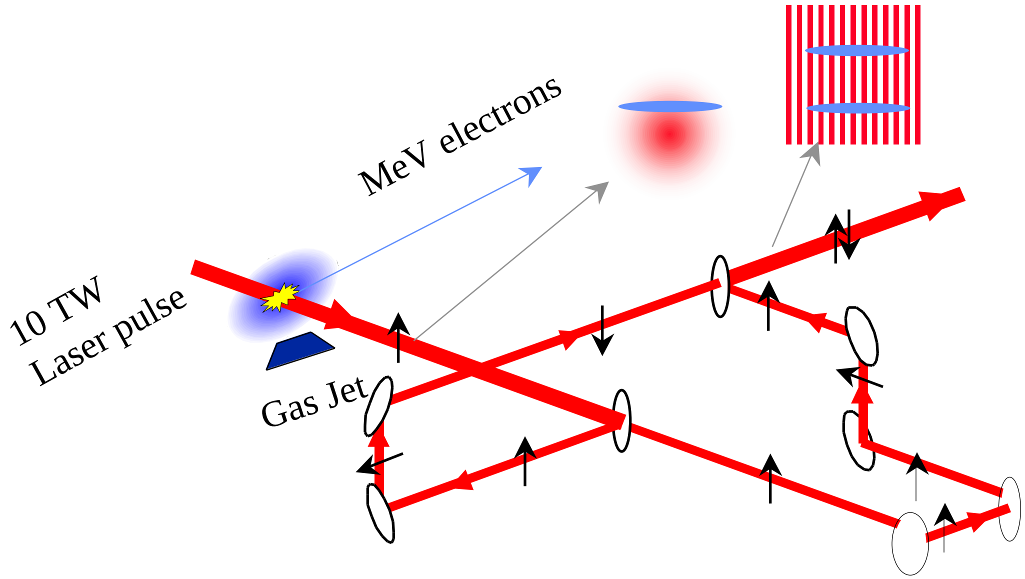
Mach-Zehnder interferometry



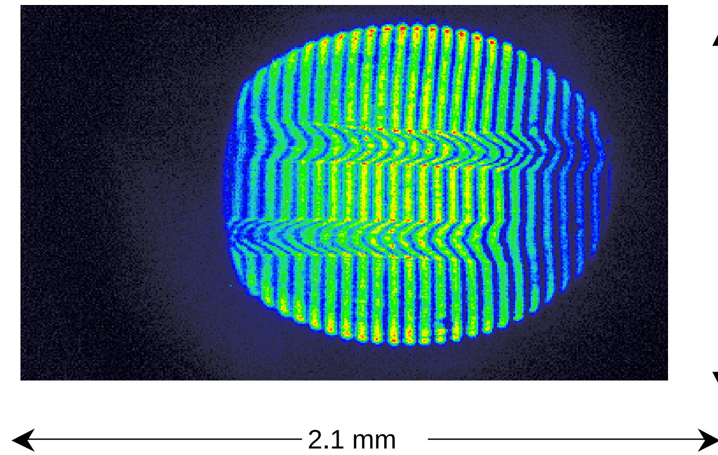
Double-pulse interferometry to measure wakefield



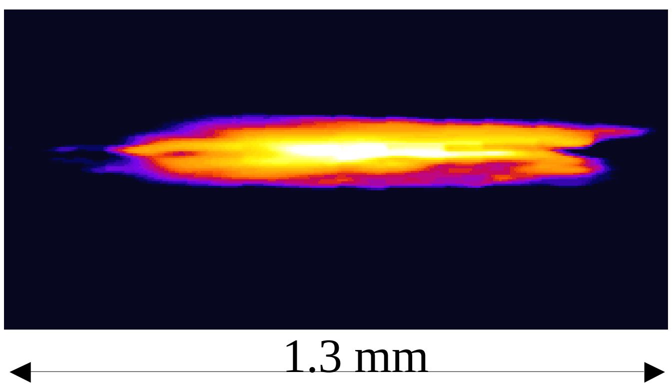
Folded-wave interferometry



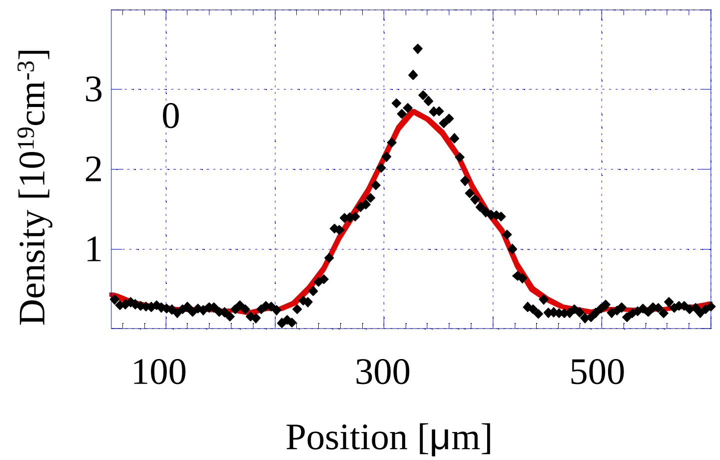
Interferogram



Electron density



Radial Profile



Outline

- **Needs ⇔ Capabilities**
- **Lasers — 102**
- **Amplification principles**
  - **— Chirped Pulse Amplification (CPA)**
- **Case studies**
  - **— multi-TW CPA systems @ LBNL, ex-UCSD**
- **Beam diagnostic tools**
- **Lasers around the globe**
- **Special acceleration related issues, future**

Example systems around the globe

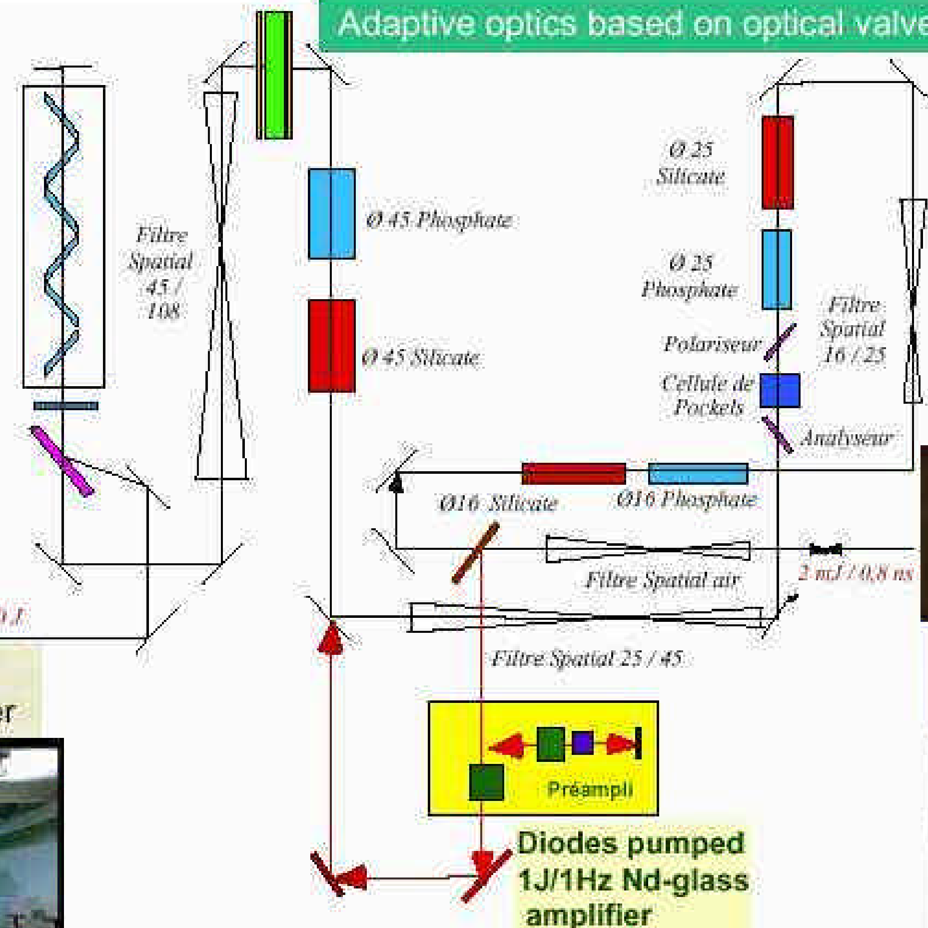
- Additional Ti:sapphire CPA lasers
  - RAL — Imperial College, UK — 100 TW
  - MBI — Berlin, Germany — 100 TW
  - CELIA — Bordeaux, France — 1 kHz, > 1 TW
  - CUOS — Michigan, MI — 30 TW, 100 TW/PW planned
  - LLNL — Livermore, CA — ex-PW, 10 TW, 100 TW planned
  - NRL — Washington, DC. — 15 TW, 25 TW planned
  - Univ. Texas — Austin, TX — 4 TW, 100 TW planned
  - Univ. Jena — Germany — 30 TW, PW planned
  - LULI — Paris, France — 100 TW, PW planned
  - JAERI — Kansai, Japan — 100 TW, PW planned
  - …
- Ultrashort pulse CO_2 lasers
  - UCLA — Los Angeles, CA — 1 TW, 100 TW planned
  - BNL-ATF — Brookhaven, NY — 20 GW, 10 TW planned
- Nd:YAG system for photocathode research
  - BNL-ATF — Brookhaven, NY
  - LLNL — Livermore, CA
  - FNAL, CERN …
- Beam-beam interactions
  - LBNL-ALS — Berkeley
  - LLNL — Livermore, CA
  - GSI — Darmstadt, Germany ...

The LULI 100TW laser

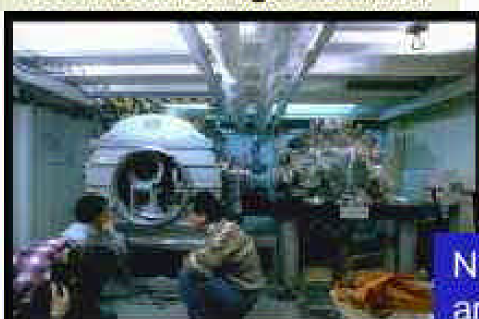
Adaptive optics based on optical valves

Ø 108 Nd Phosphate glass disk amplifier

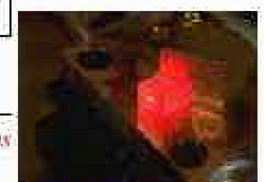
30J - 300 fs
+ 1J - 300fs
+ 60J - 0.8ns



Compressor stage in vacuum and target chamber



Diodes pumped 1J/1Hz Nd-glass amplifier



Ti:Saph oscillator + regeneratif amplifier

New concepts of high fluence and high efficiency gratings

Phase and amplitude control using an AOPDF

Courtesy of C. LeBlanc, LULI, France

The LULI 2000 program

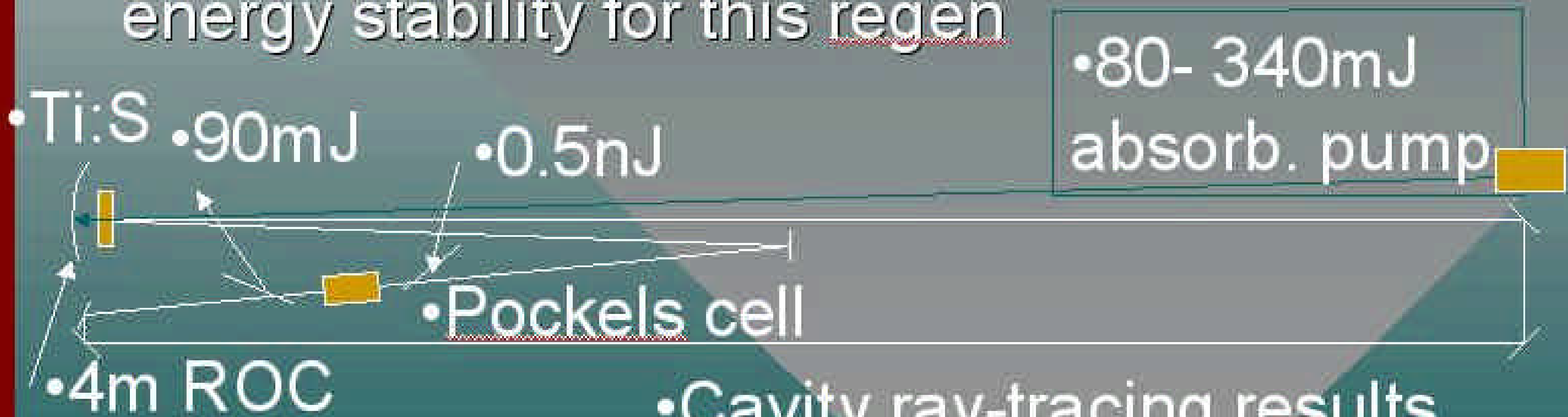
- Two «kilojoule»chains : the *LULI nano 2000* project
- Four «100 J» chains
- Three regimes :
  - nanosecond : 1 ns - 5 ns,
  - picosecond : 100 ps - 1000 ps, ***LULI pico 2000***
  - femtosecond : 500 fs - ps : ***The Petawatt laser***

	Date	Energy J	Duration ps	Power TW	Intensity W/cm^2	Rep. Rate
kJ - ns	2002	2 x 1000	2000	2	10^{17}	1 shot per hour
PW laser	2003	1 x 500	0,5	1000	$> 10^{22}$	1 shot per hour

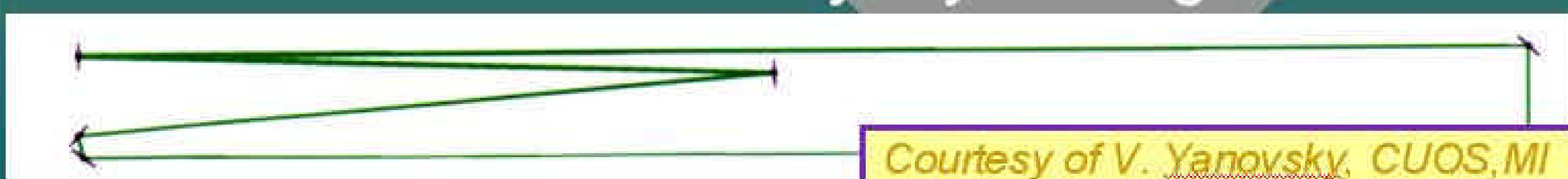
Courtesy of C. LeBlanc, LULI, France

High-energy-large-mode regenerative amplifier

- Regenerative amplifier vs multipass amplifier
- Advantage: superior beam quality, stability better than pump- we measured 0.5% RMS energy stability for this regen

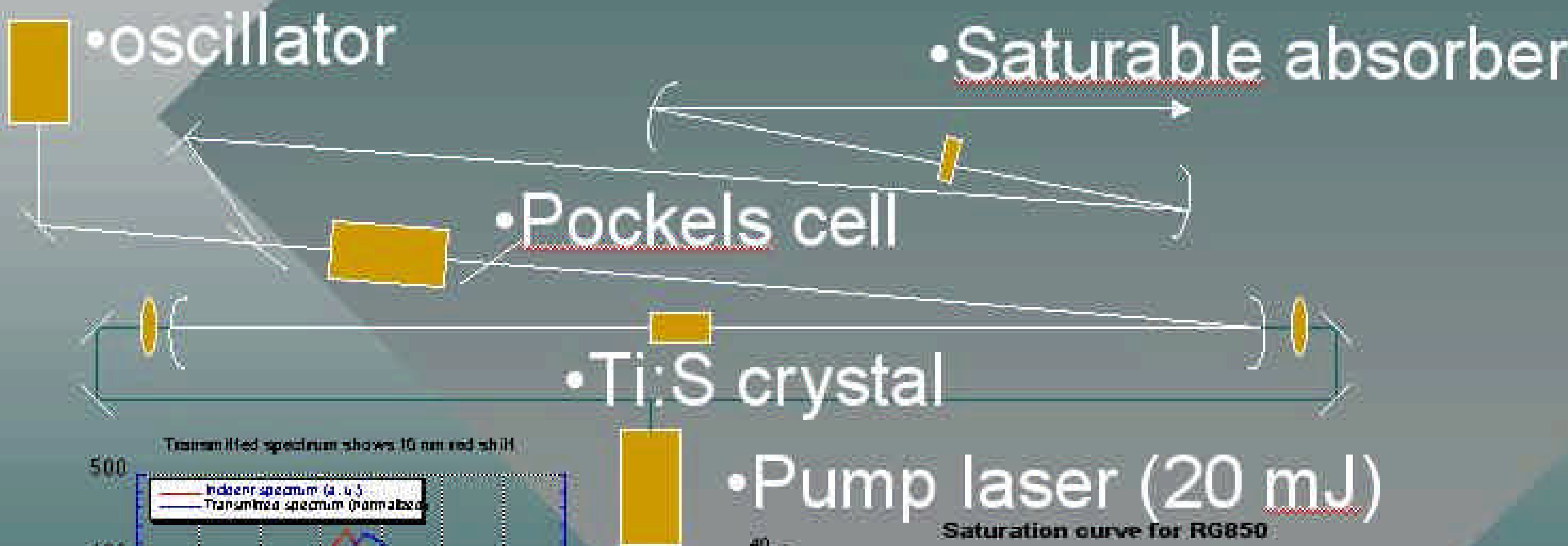


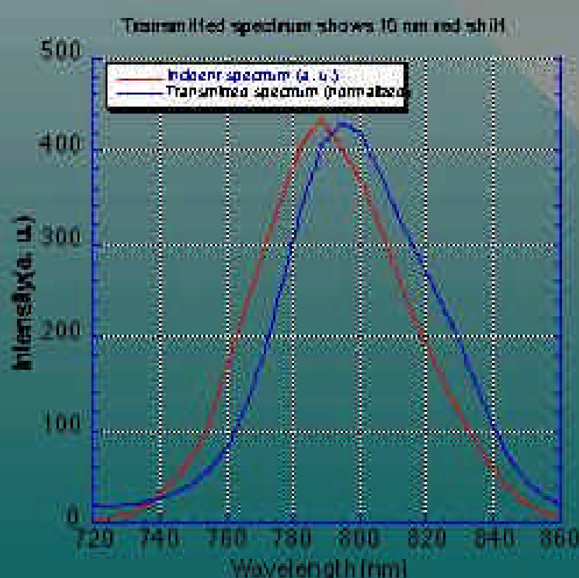
•Cavity ray-tracing results

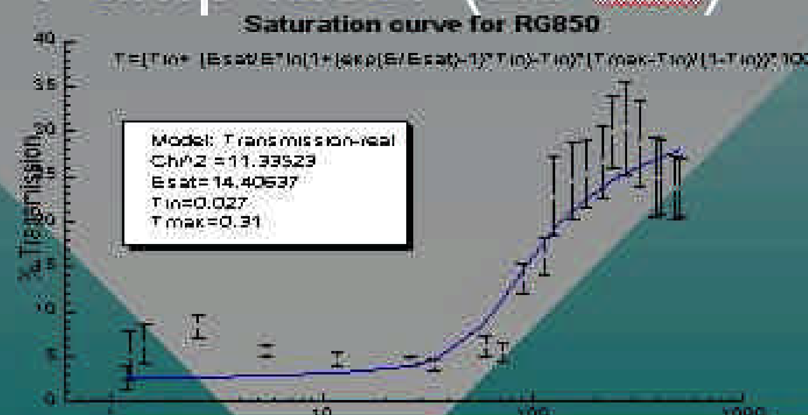


Courtesy of V. Yanovsky, CUOS,MI

Preamplifier and cleaner







Courtesy of V. Yanovsky, CUOS,MI

T^3 Upgrade parameters

Wavelength	**1.053 μm**
Stretched pulse energy	**up to 8 J (12.5 J)***
Pulse length	**400 fs**
Compressed pulse energy	**up to 6 J (10 J)***
Peak power	**Up to 15 TW (25 TW)***
Diffraction limit	**~ 1.2x**

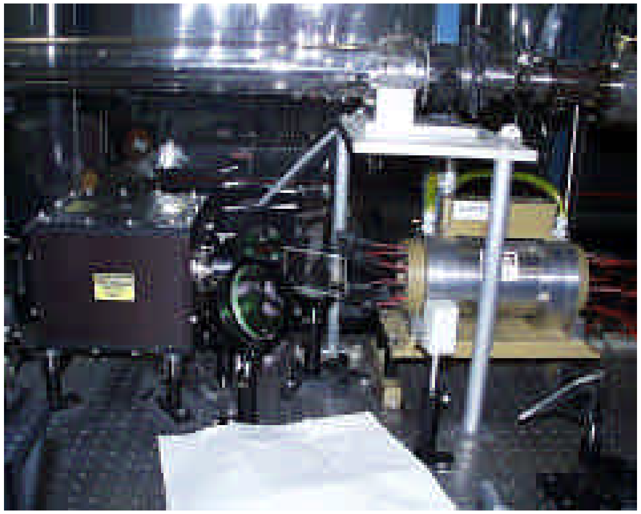
***Values in parenthesis can be reached but have not been fired**

Courtesy of T. Ting, NRL

T^3 Upgrade

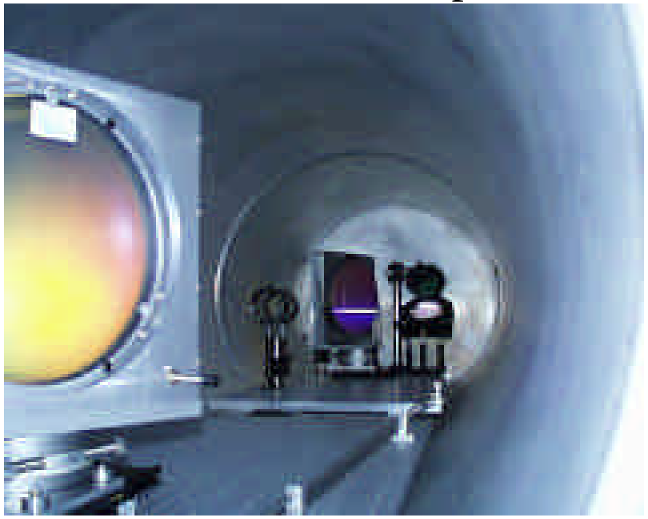
NRL
Plasma Physics Division

45 mm Nd:Glass amplifier



Vacuum compressor chamber

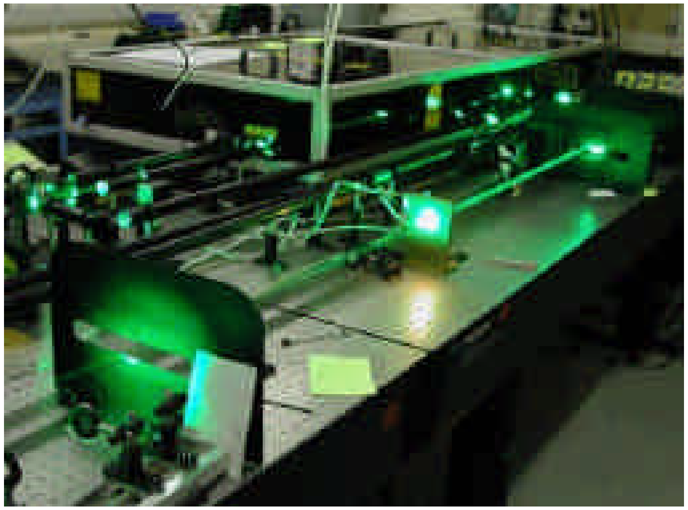
Inside vacuum compressor



Experimental chamber and diagnostics

Courtesy of T. Ting, NRL

ASTRA



Wavelength 750-850nm

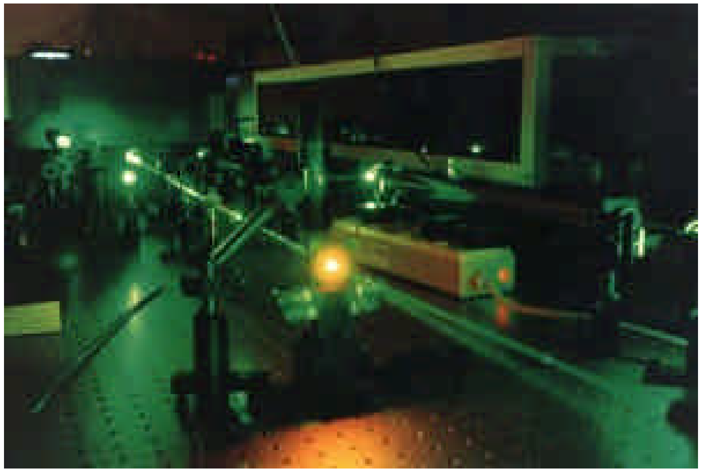
Pulse length 50 fs

Energy/pulse 500 mJ

Power 10 TW

Focused Intensity 1 x 10^{19} W cm^{-2}

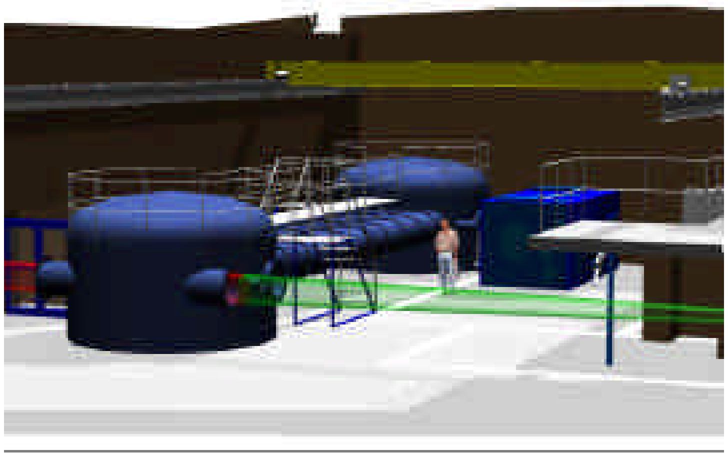
Repetition Rate 1 Hz



Courtesy of H. Hutchinson, Imperial College - RAL, UK

VULCAN

8 Beam Nd:glass laser
3 kJ long pulse
100 TW, 10 ^{20} W.cm^{-2}
2 separate target areas

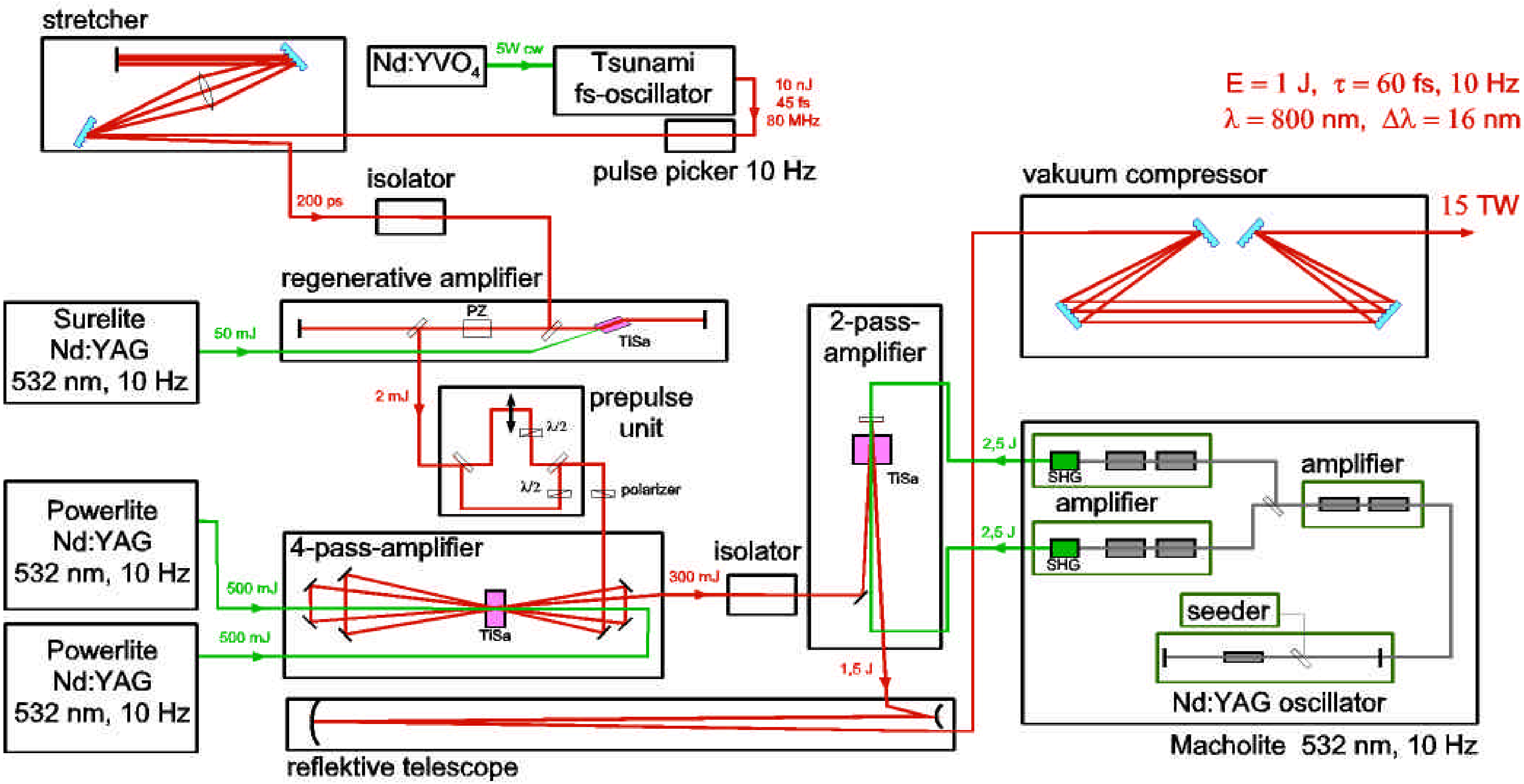


June 2002 - 1 PW facility completed
500J / 500 fsec
10^{21} Wcm^{-2}

multi-PW operation using OPCPA under active investigation

Courtesy of H. Hutchinson, Imperial College - RAL, UK

Jena multi - TW - Ti:Sapphire - laser system



Courtesy of R. Sauerbrey, Jena, Germany

POLARIS-System

oscillator, stretcher 100 fs   2 ns, preamplifier

regenerative amplifier V-1:
4 laser diode bars: 200 mJ

regenerative amplifier V0:
4 laser diode stacks: 13 J

multi pass amplifier V1:
20 laser diode stacks: 100 J

multi pass amplifier V2:
200 laser diode stacks: 1 kJ

compressor
1 PW

1 mJ → 25 mJ → 2 J → 20 J → 200 J → 150 J

Advantages

- short pulses
- repetition rate 0.1 Hz
- table top system 100 m_
- energy stability

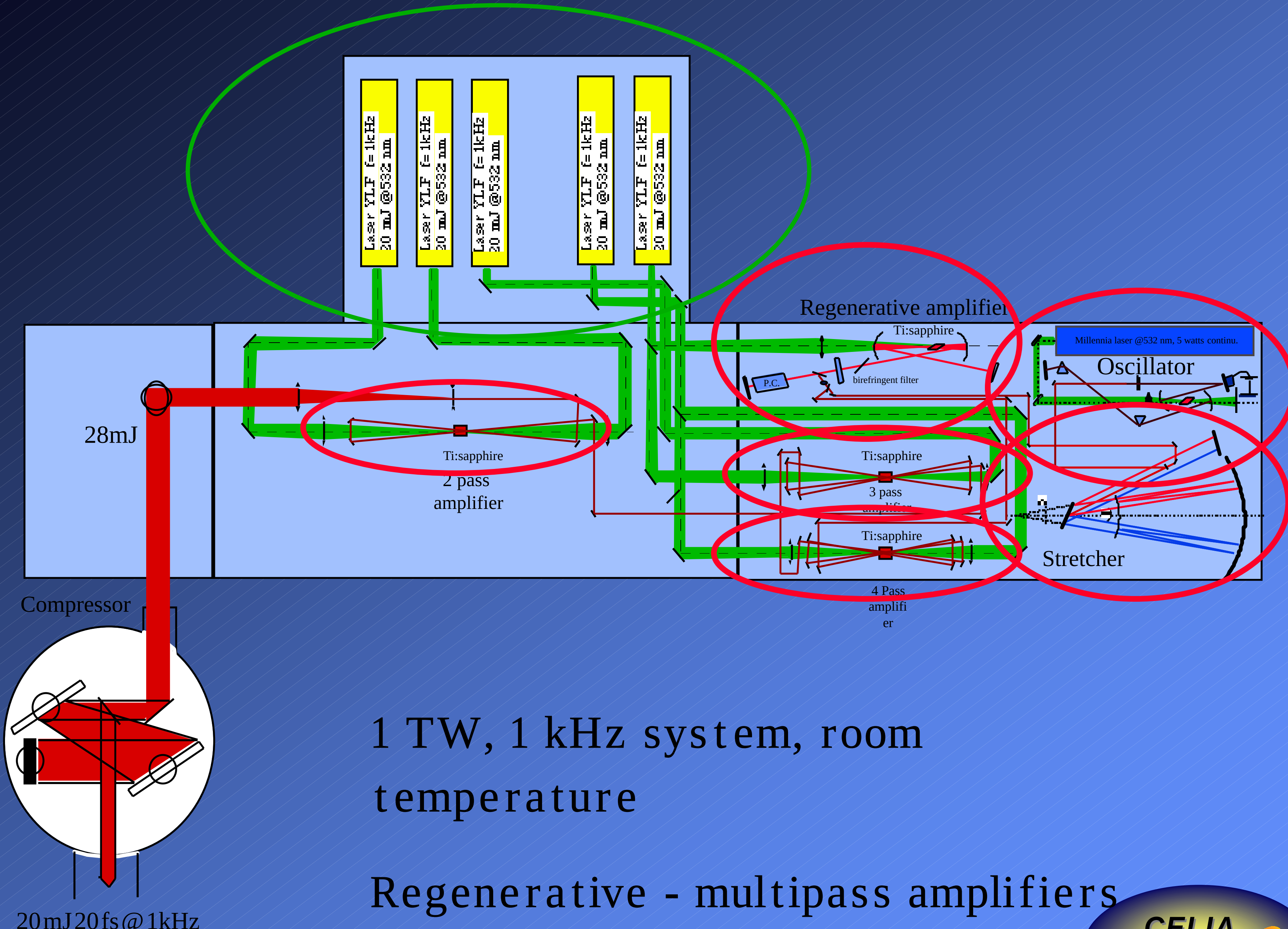
Requirements

- 4500 laser diode bars
- 100 cm^3 FP-Glass
- laser damage resistent optical components
- with high finesse

Courtesy of R. Sauerbrey, Jena, Germany

New Japanese CPA Facility

- **Advanced Photon Research Center near Nara Japan**
- **~150 scientists, 4 large experimental bays, and 2 main CPA laser systems**



1 TW, 1 kHz system, room temperature

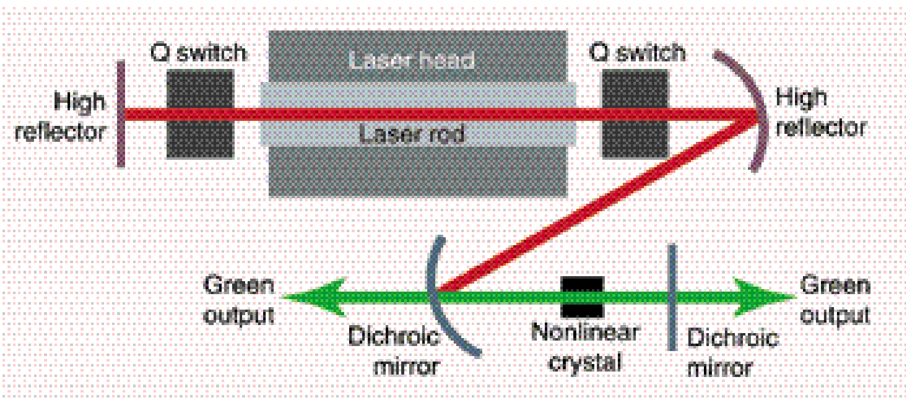
Regenerative - multipass amplifiers

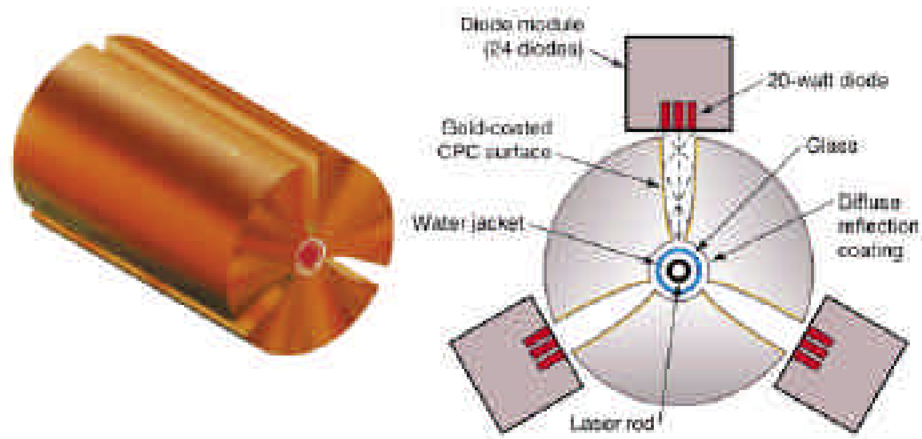
CELIA

Courtesy of F. Salin, Bordeaux, France

High average power pump lasers are essential for development of high power solid state lasers

- High average power short pulse lasers require high power pump lasers
- Example: Diode pumped system developed by Jim Chang et al. (LLNL)
- Provides > 300 W , 532 nm @ 10 to 20 kHz.



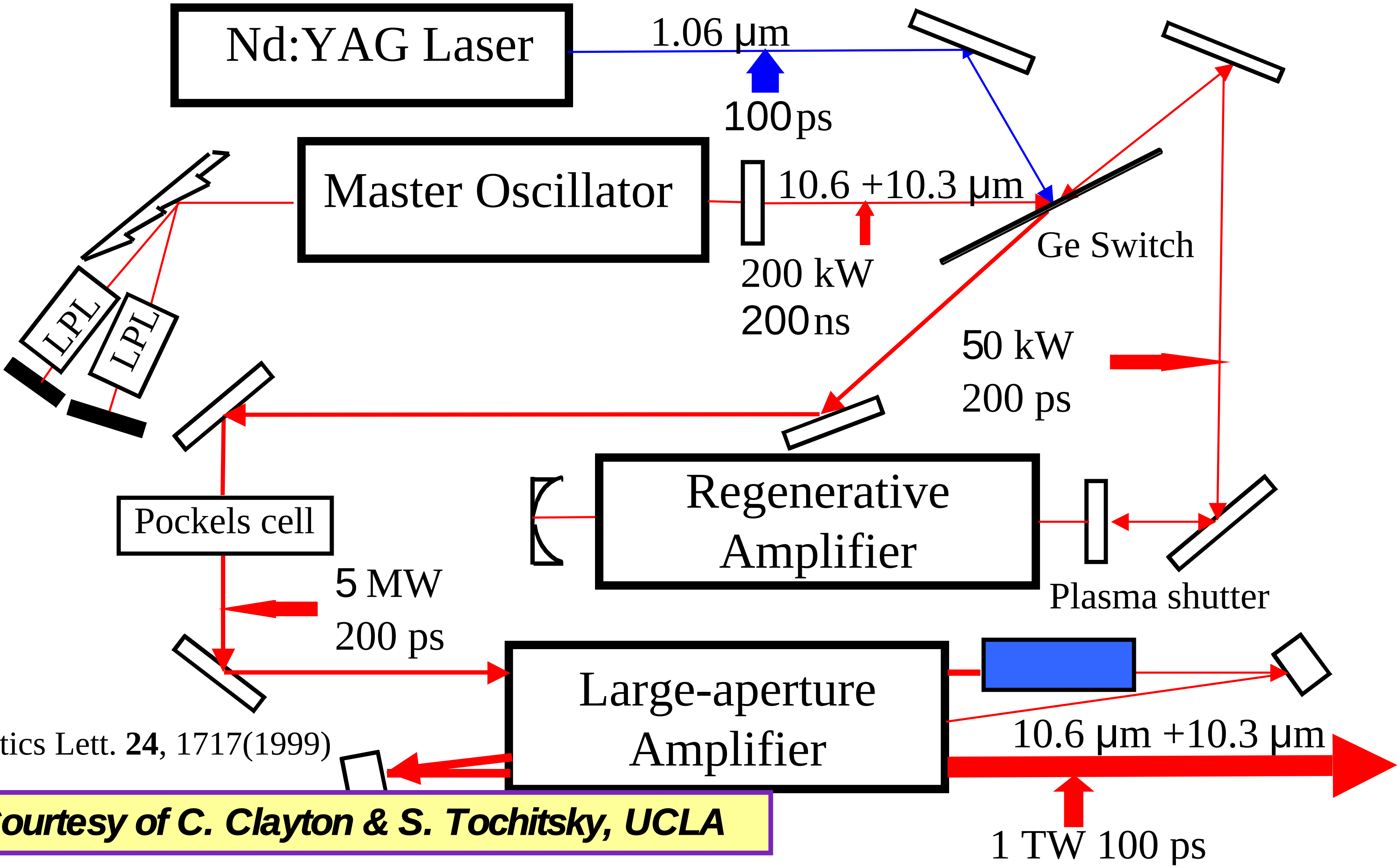


Schematic of the diode-pumped solid-state green laser (DPSSGL) pumping concept. Light from a diode is compressed by the compound parabolic concentrator (CPC) through a small slit into the chamber surrounding the laser rod. There, the rod absorbs the diode light and converts it into infrared laser light.

- **Compound parabolic concentrator (CPC)**
- **CPC converts > 40 % diode radiation into IR light**
- **Optical system converts 75 to 80 % into green output**

http://www.llnl.gov/str/Chang.html

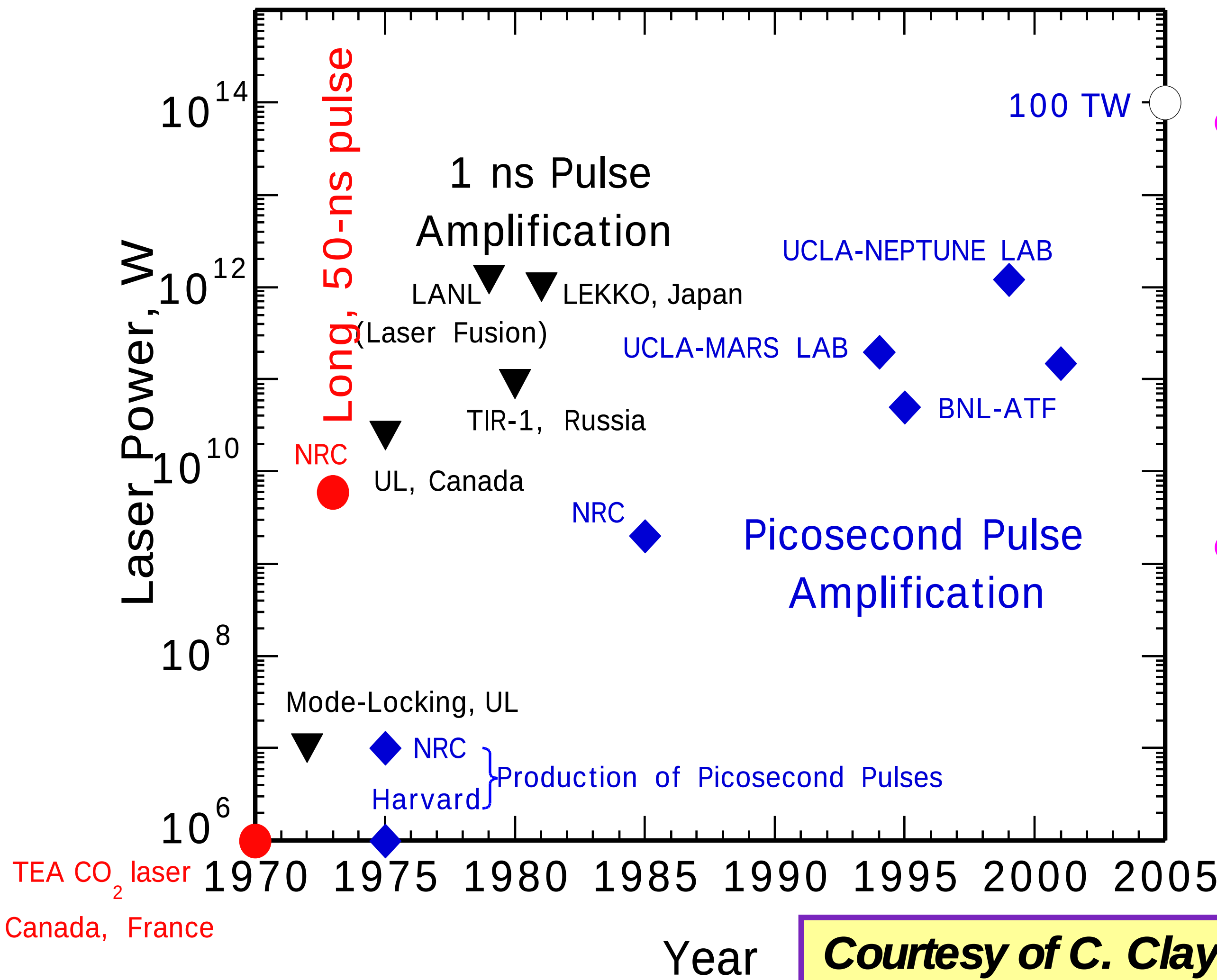
Neptune TW CO_2 Laser System



Optics Lett. **24**, 1717(1999)

Courtesy of C. Clayton & S. Tochitsky, UCLA

10-μm Power Source for High-Field Physics



- LLNL - 1999
  Petawatt Nd:Glass Laser
  λ=1.06 μm
  I ≈ 6 x 10 ^{20} W/cm^2
  Vosc/c ≈ 19

- NEPTUNE - 200?
  100 TW CO_2 Laser
  λ=10.6 μm
  E ~ 100 J in 1 ps
  I ≈ 8 x 10^{18} W/cm^2
  Vosc/c ≈ 20

Courtesy of C. Clayton & S. Tochitsky, UCLA

Brookhaven Accelerator Test Facility

Nd:YAG Photoinjector Drive Laser

- Electron beam-synchronized optical pulses available for facility users:
  10 mJ, 14 ps @ 1064 nm in laser lab
  100 μJ, 10 ps @ 532 nm in laser lab or FEL room
  50 μJ, 8 ps @ 266 nm in gun hutch and laser lab

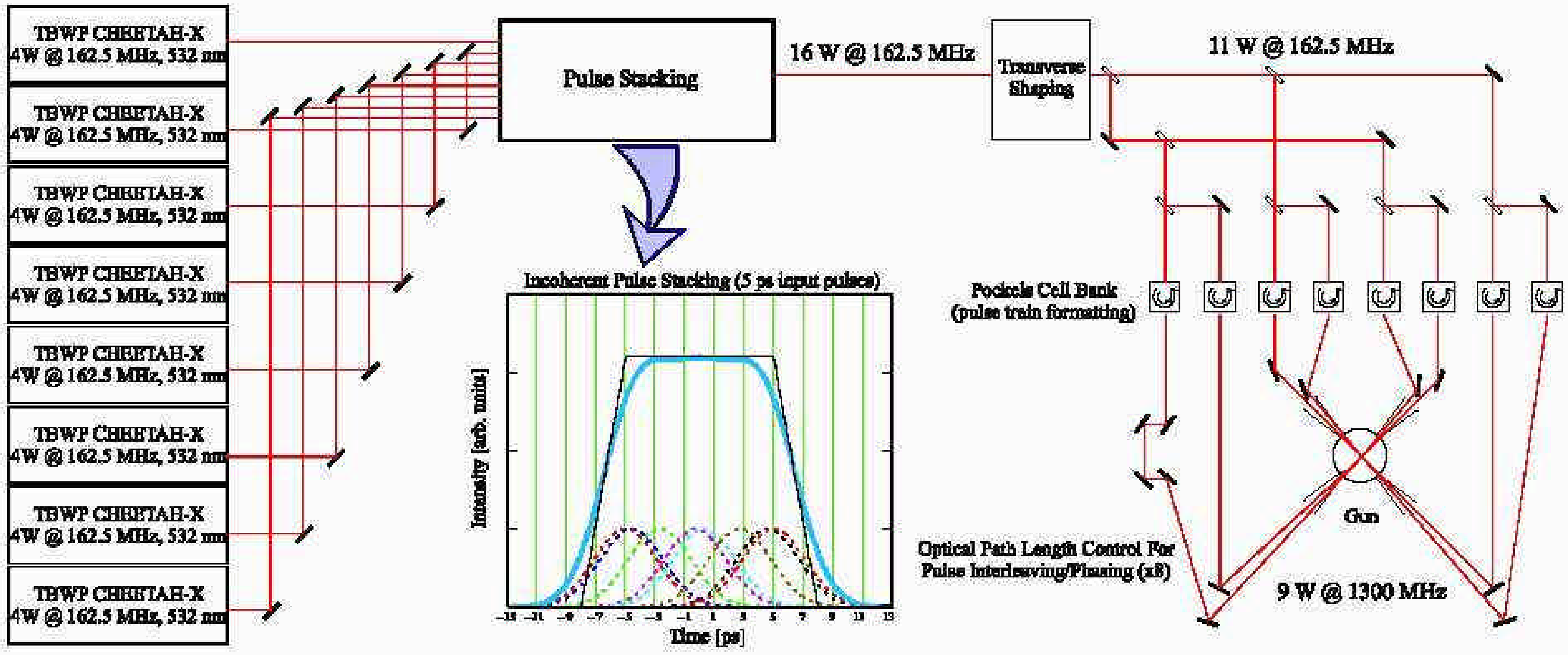
- Exceptional system availability: deliver light ~130 days/year, for a total of 1500 running hours.

- High reliability: system typically ready for electron gun operation within 20 minutes, including daily performance characterization.
- Routinely demonstrates parameters sufficient for high-brightness electron beam R&D in FEL's, beam transport studies, laser particle accelerators, and advanced electron beam diagnostics:

Energy on cathode (@ 266 nm)	0-50 μJ
total IR (in two pulses)	30 mJ
Repetition rate	1.5, 3 Hz
Pulse duration (gaussian-FWHM @ 266 nm):	8 ps
Beam Profile Variation from Ideal Top-Ha (P-P)	<20%
Shot-to-shot stability (rms over 5 minutes):	
Timing	<0.2 ps
Energy	<2 %
Pointing (fraction of beam)	<0.3 %
Drift (P-P over 8 hours)	
Timing	<1ps
Energy	<15 %
Pointing (fraction of beam)	<1%

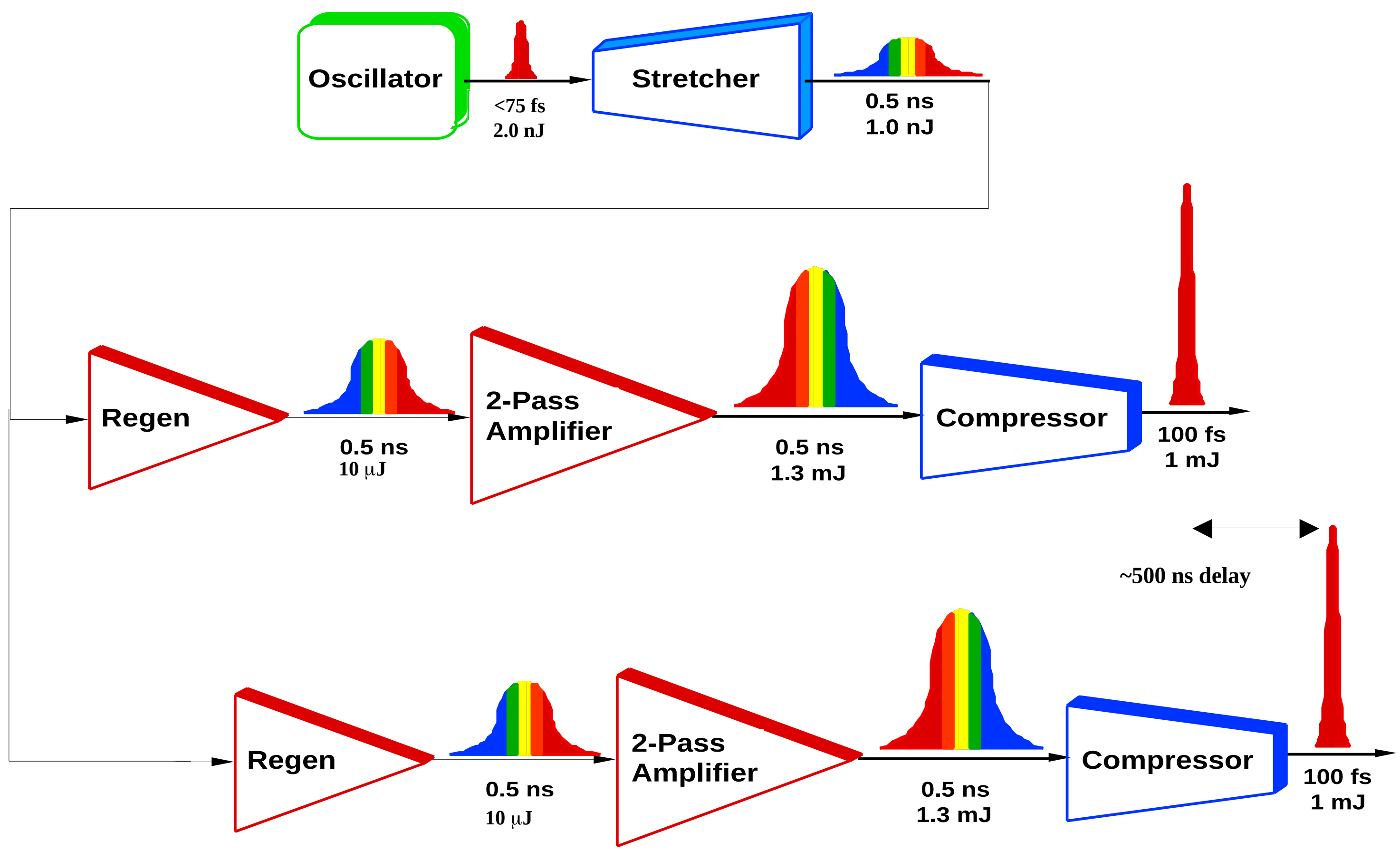
Courtesy of M. Babzien

Proposed PERL Drive Laser Block Diagram



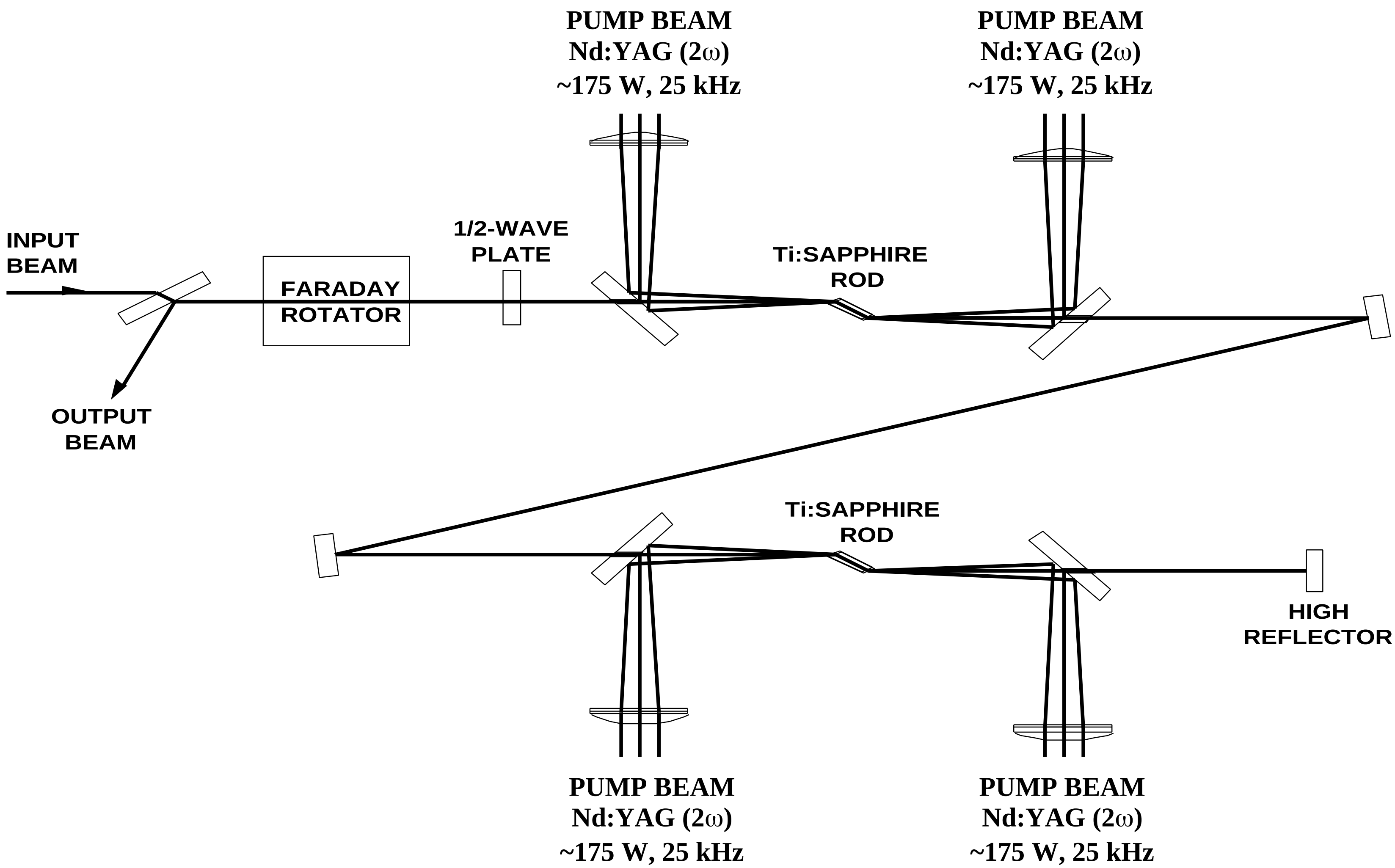
Courtesy of M. Babzien & T. Srinivasan-Rao, BNL

Regenerative amplifier pair for pump-probe studies LBNL-ALS



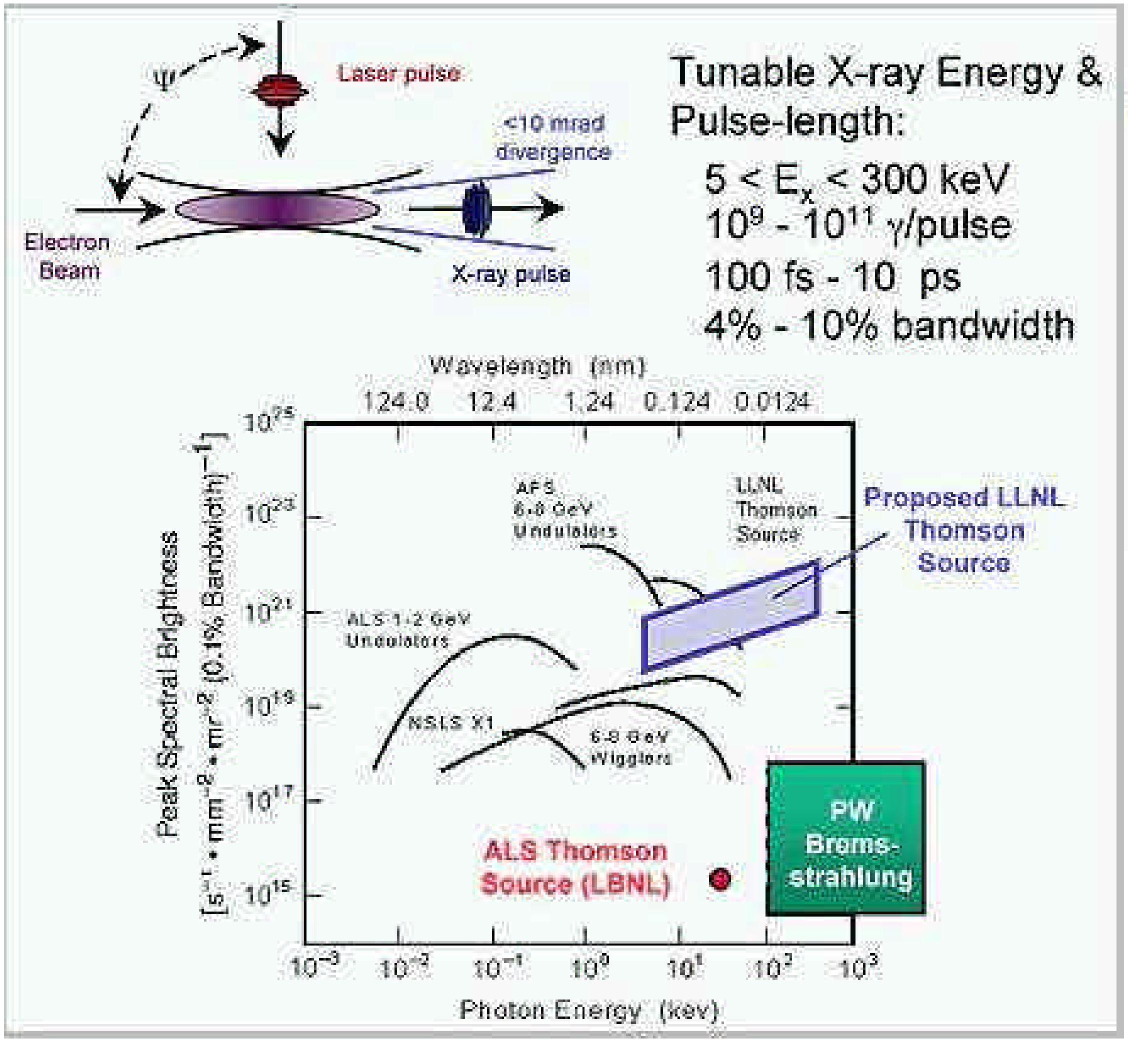
Courtesy of R. Schoenlein, LBNL

Cryogenically cooled regenerative amplifier
LBNL-ALS



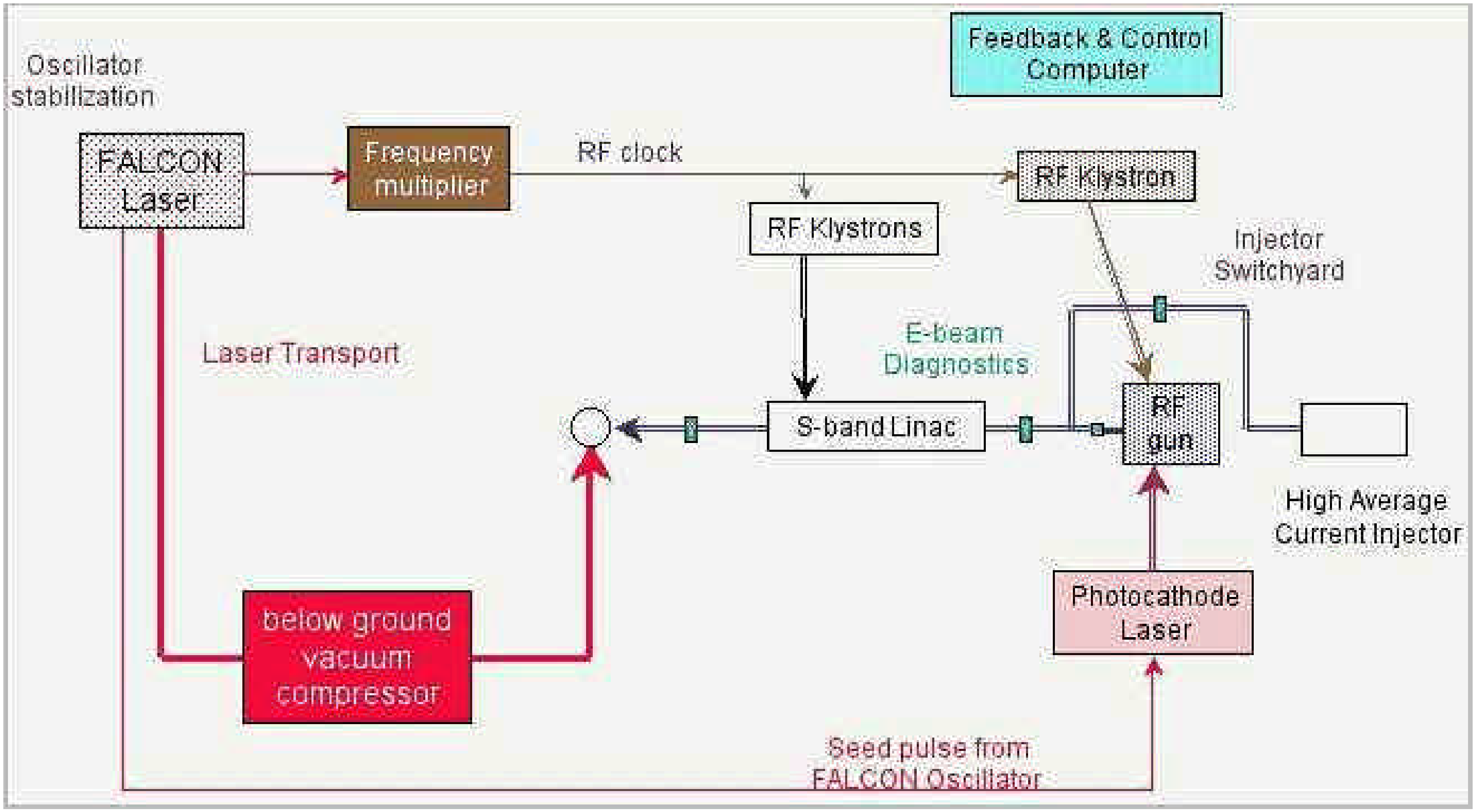
Courtesy of R. Schoenlein, LBNL

Intense Laser-Electron Interactions - LLNL -Livermore



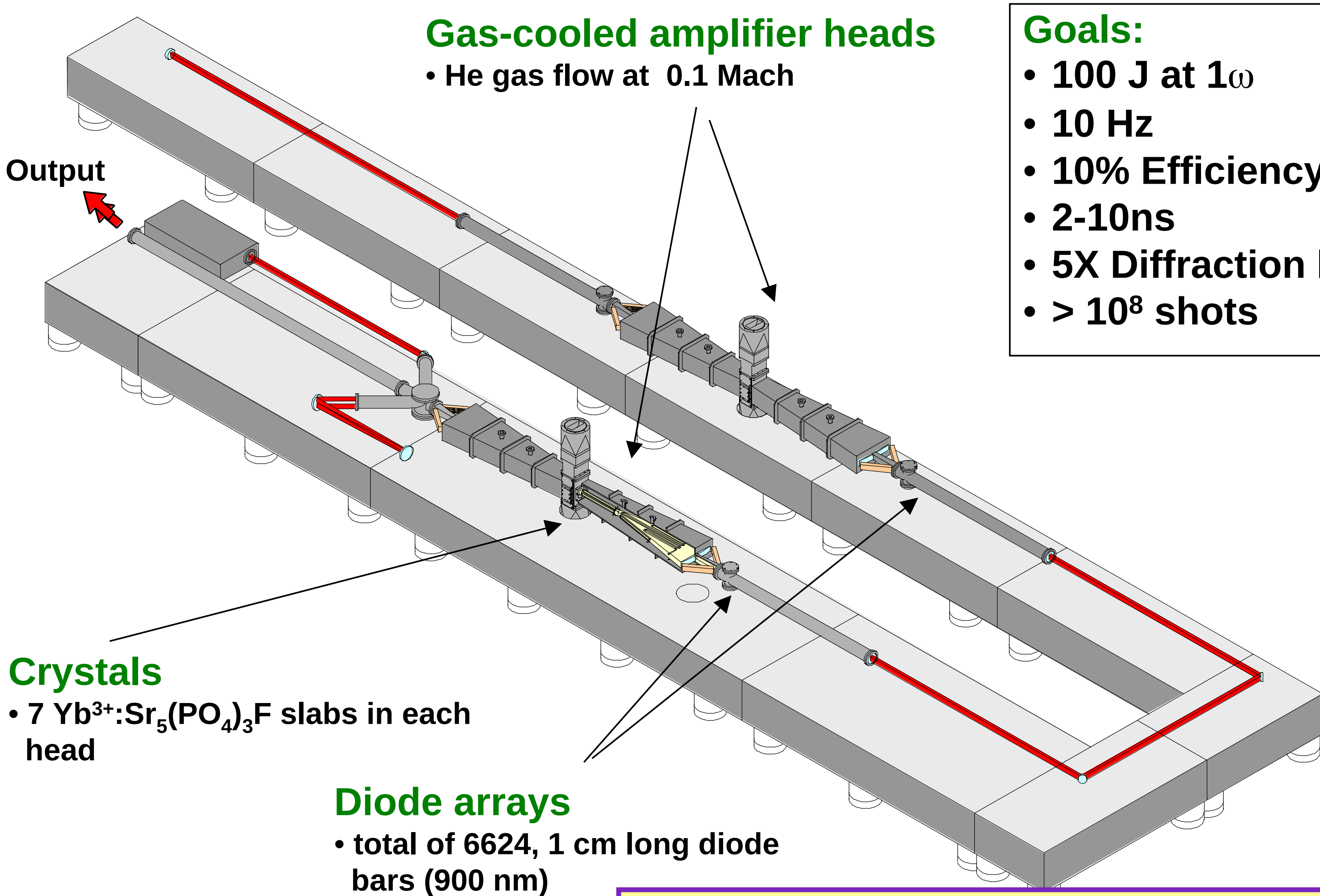
http://www-phys.llnl.gov/Organization/HDivision/Research/LINAC/LINACFacilityVirtualTour/

Intense Laser-Electron Interactions - LLNL -Livermore



http://www-phys.llnl.gov/Organization/HDivision/Research/LINAC/LINACFacilityVirtualTour/

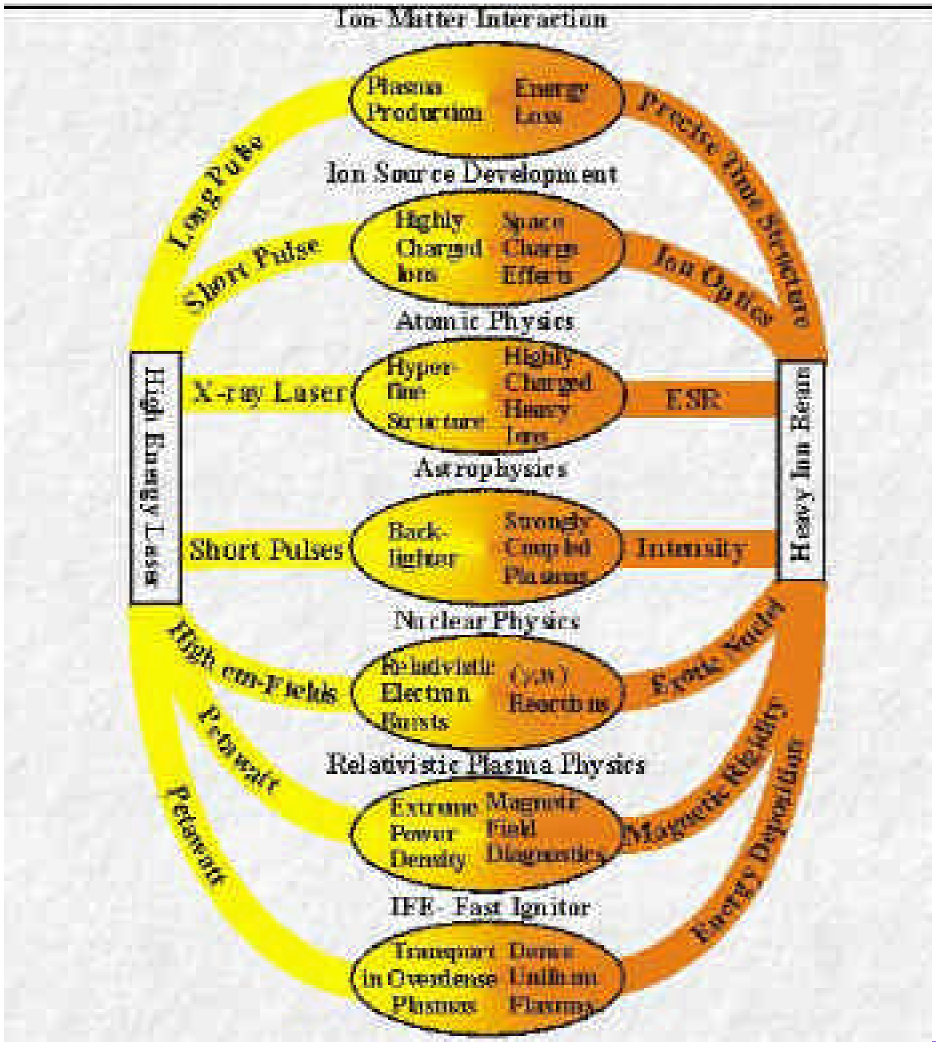
LLNL Mercury Laser: 1kW demo



Goals:
- 100 J at 1ω
- 10 Hz
- 10% Efficiency
- 2-10ns
- 5X Diffraction limit
- > 10^8 shots

http://lasers.llnl.gov/lst/advanced.html

Laser - ion beam interactions at GSI-Darmstadt



PHELIX

*P*etawatt *H*igh-*E*nergy *L*aser for Heavy-*I*on E*X*periments

http://www-aix.gsi.de/~phelix/

Outline

- Needs ⇔ Capabilities
- Lasers — 102
- Amplification principles
  - — Chirped Pulse Amplification (CPA)
- Case studies
  - — multi-TW CPA systems @ LBNL, ex-UCSD
- Beam diagnostic tools
- Lasers around the globe
- Special acceleration related issues, future

Practical issues, future

- Reliability
  - Technology must be risk free
  - Remote control
  - System integration
- Lifetime
  - Critical components:
    - Nonlinear crystals
    - Laser crystals
    - Compressor grating
- Cost
  - Price of pump lasers should decrease
- Size
  - Size of pump lasers should decrease

Evolution of CPA Utility

- **Ti:sapphire systems operate at high rep rate AND peak power**

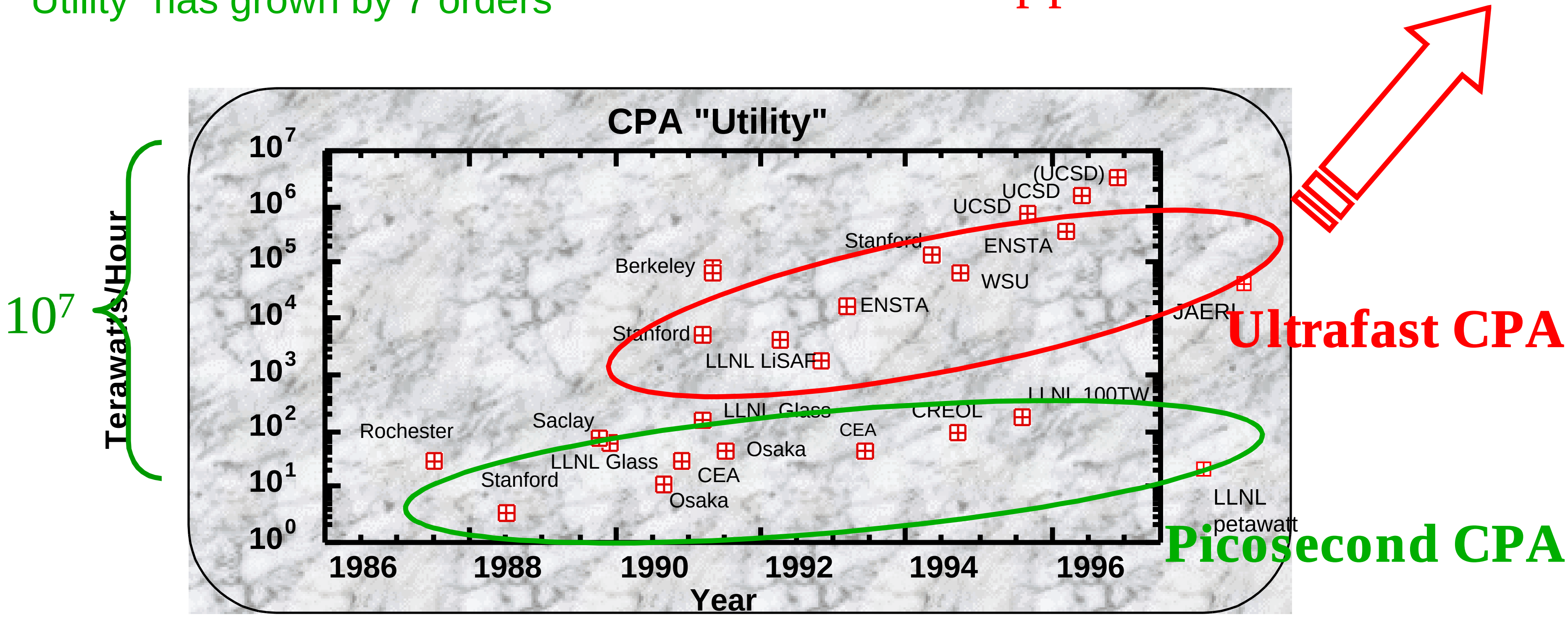
❍Peak Power times Rep Rate or

“Utility” has grown by 7 orders

❍Present Practical Limits:

Peak power :	**3 orders**
Pulse duration :	**factor of 2**
Average pump power :	**3-4 orders**

Approx. 7 Orders Left



Courtesy of Chris P.J.Barty

Logo-s