Textbook:

Fundamentals of Photonics

(Author: B.E.A. Saleh and M. C. Teich)

Reference book:

1. Nonlinear Fiber optics
2. Applications of Nonlinear Fiber Optics

(Author: G. P. Agrawal)

上課時間

Thursday 5, 6, 7

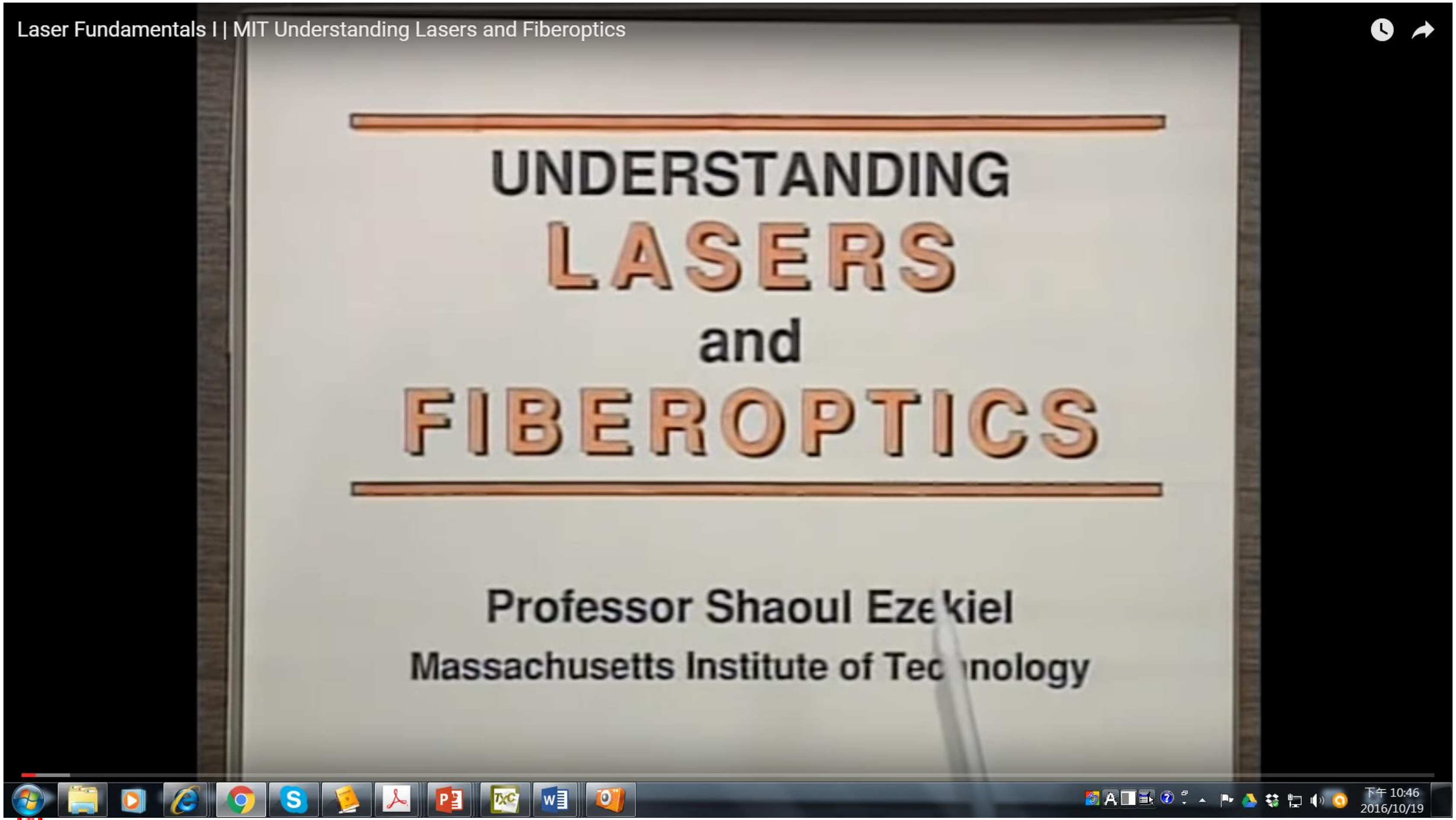
評分標準： 1. 平時分數 10%（出席率，聽講，發問）

2. 期中考試 45%

3. 期末報告 45%

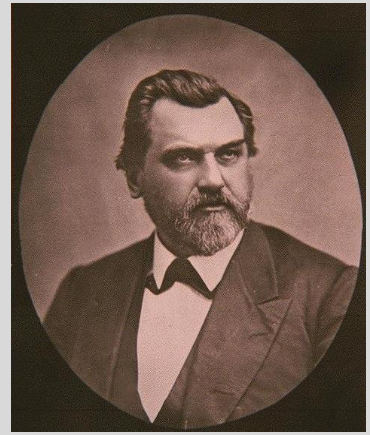
Understanding Lasers

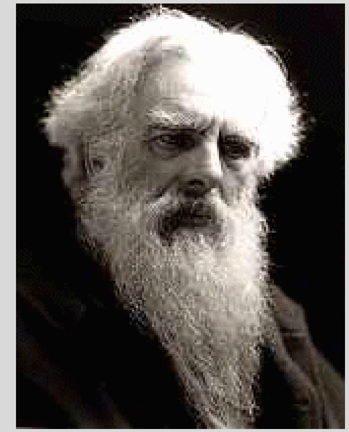
- https://www.youtube.com/watch?v=saVE7pMhaxk

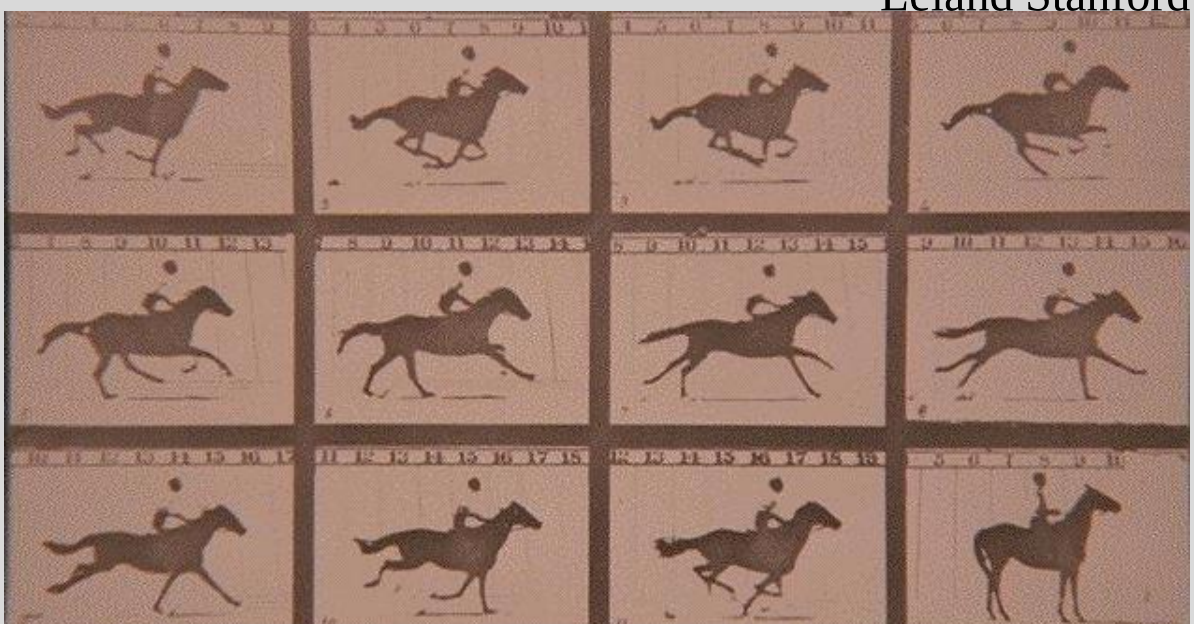


The Birth of Ultrafast Technology

Bet: Do all four hooves of a galloping horse ever simultaneously leave the ground?


Leland Stanford


Eadweard Muybridge



The "Galloping Horse" Controversy Palo Alto, CA 1872

Time Resolution:
1/60th of a second

- https://zh.wikipedia.org/wiki/%E5%9F%83%E5%BE%B7%E6%B2%83%E5%BE%B7%C2%B7%E8%BF%88%E5%B8%83%E9%87%8C%E5%A5%87

Horse In Motion: 1878 - Present

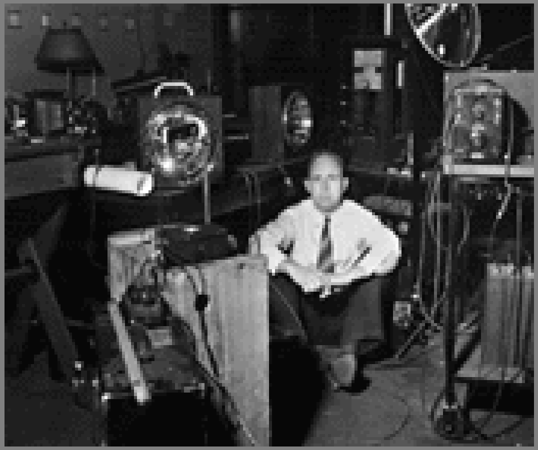
- https://www.youtube.com/watch?v=DLHDHOeJvdI

- https://www.youtube.com/watch?v=5Awo-P3t4Ho

If you think you know fast, think again.

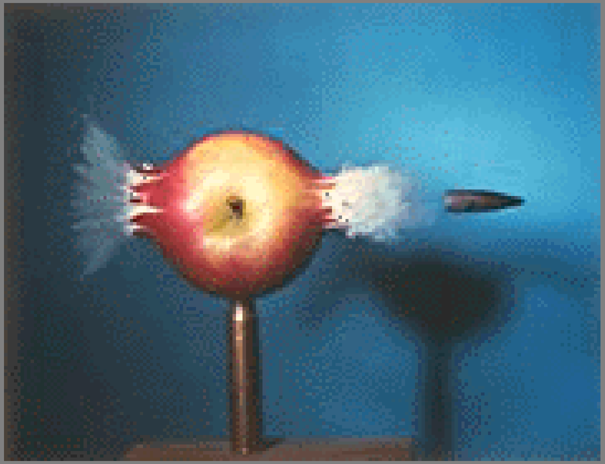
Ultrashort laser pulses are the shortest events ever created.

Strobe Photography



Harold
Edgerton
MIT, 1942

"How to Make
Apple sauce
at MIT"
1964



"Splash on a
Glass"
Junior High
School student
1996

Time Resolution: a few microseconds

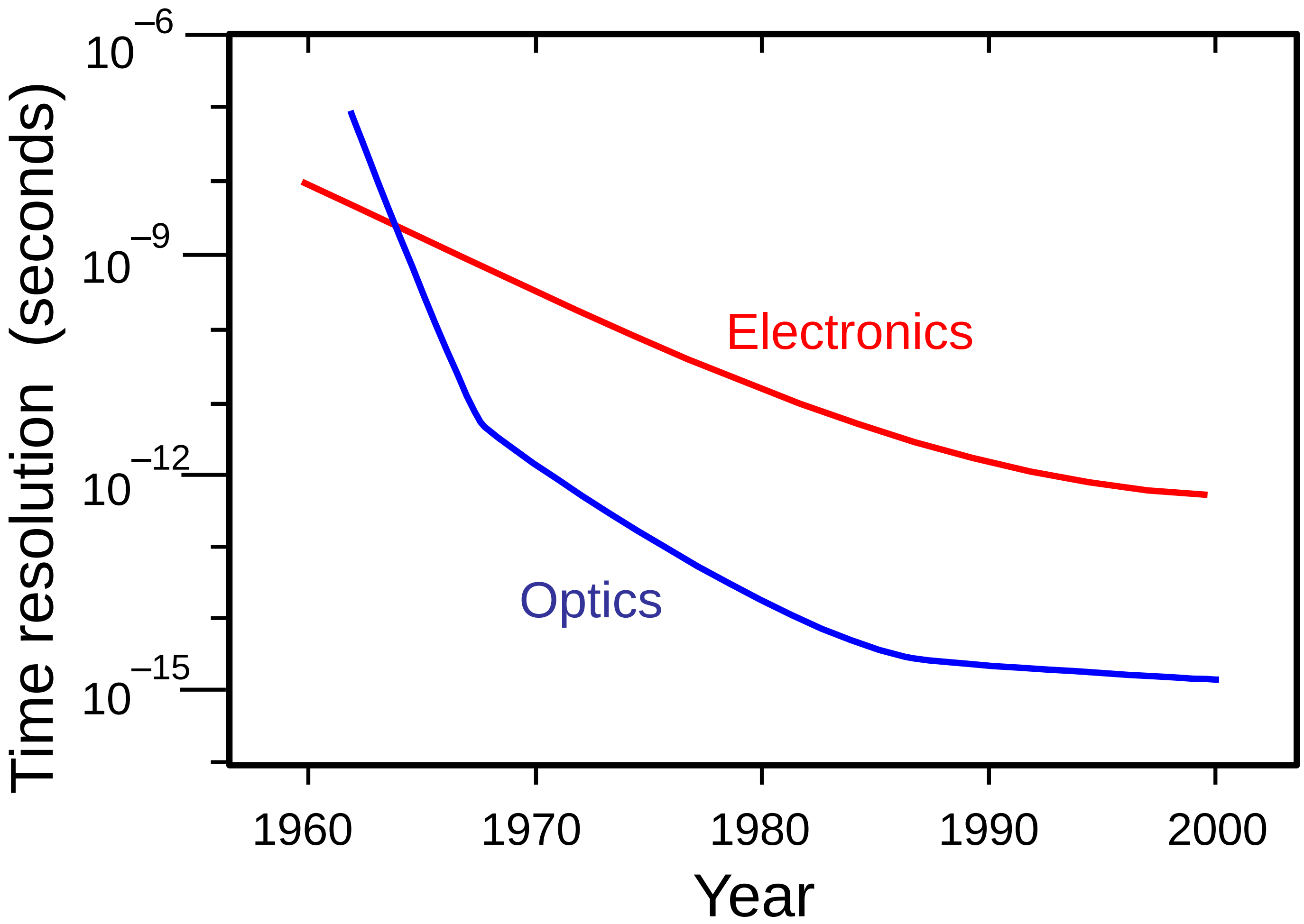
The Metric System

We'll need to really know the metric system because the pulses are incredibly short and the powers and intensities can be incredibly high.

Prefixes:

Small		Big	
Milli (m)	10^{-3}	Kilo (k)	10^{+3}
Micro (μ)	10^{-6}	Mega (M)	10^{+6}
Nano (n)	10^{-9}	Giga (G)	10^{+9}
Pico (p)	10^{-12}	Tera (T)	10^{+12}
Femto (f)	10^{-15}	Peta (P)	10^{+15}
Atto (a)	10^{-18}	Exta (E)	10^{+18}

Ultrafast Optics vs. Electronics

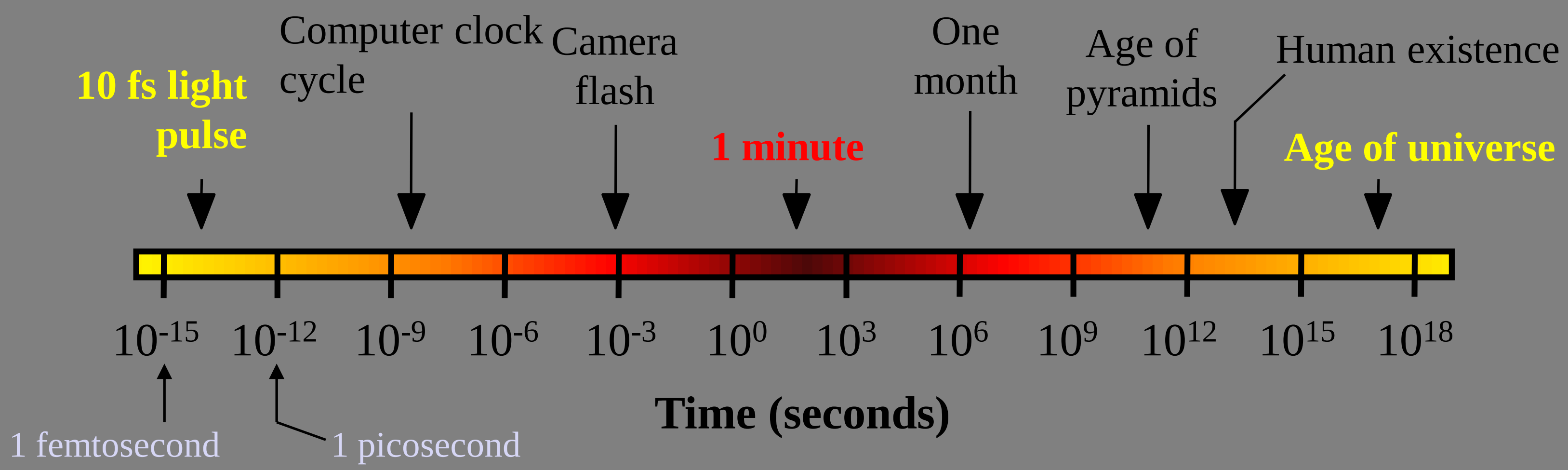


No one expects electronics to ever catch up.

Timescales

It's routine to generate pulses < 1 picosecond (10^{-12} s).

Researchers generate pulses a few femtoseconds (10^{-15} s) long.

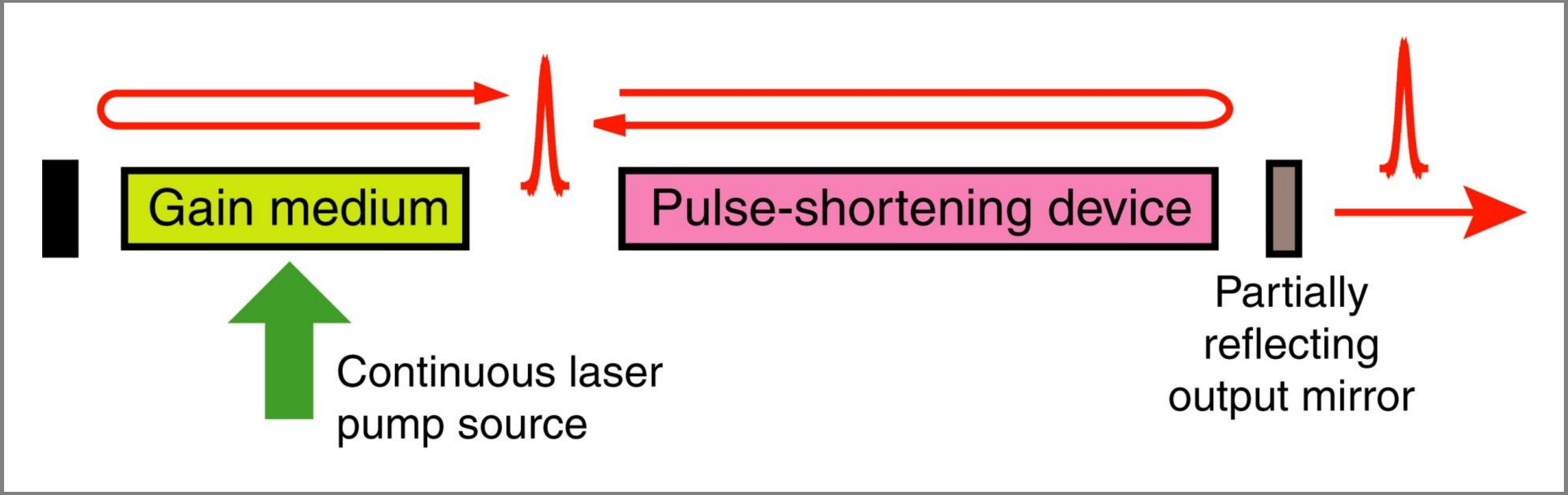


Such a pulse is to one minute as one minute is to the age of the universe.

Such a pulse is to one second as 5 cents is to the US national debt.

A generic ultrashort-pulse laser

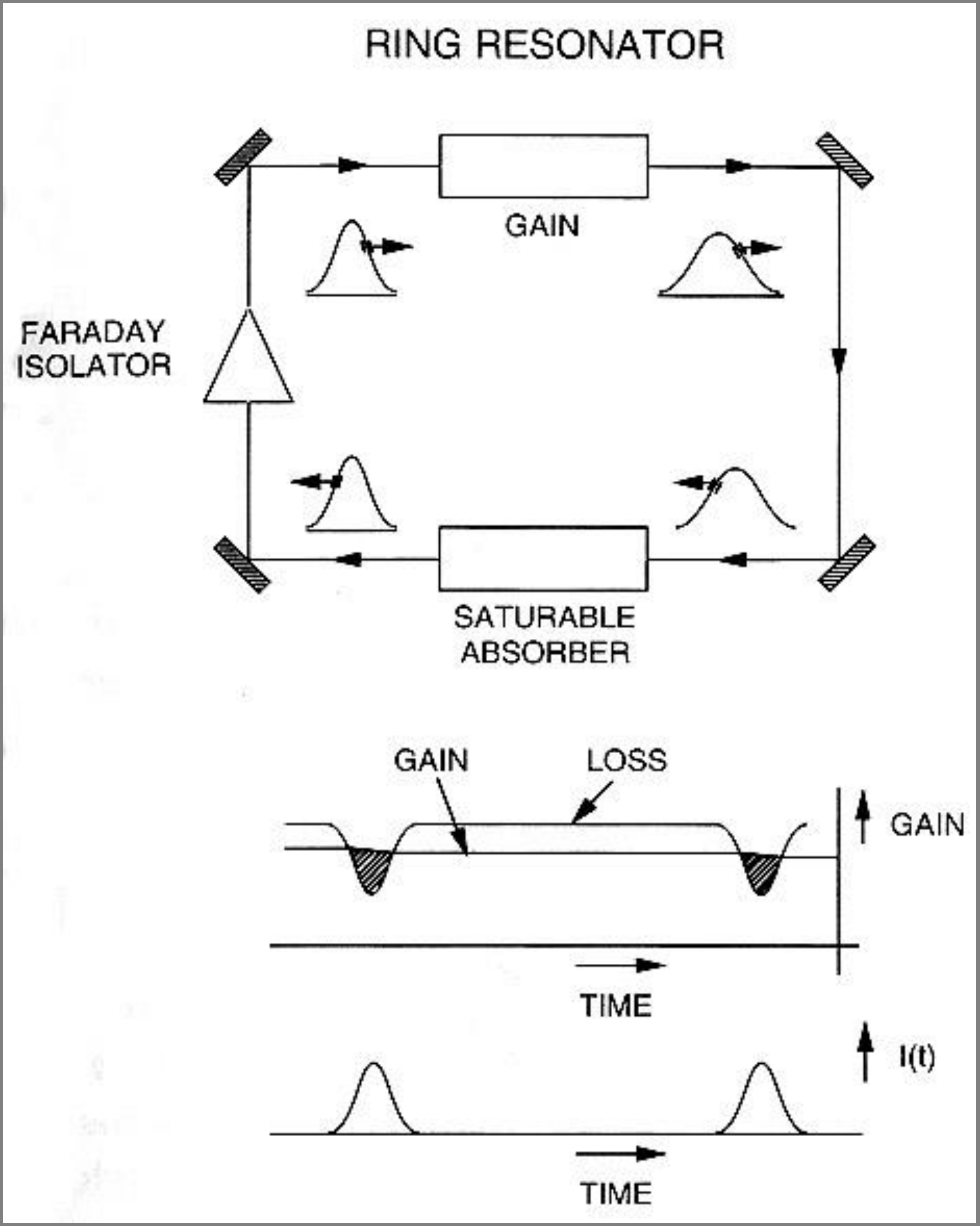
A generic ultrafast laser has a broadband gain medium,a pulse-shortening device, and two or more mirrors:



Pulse-shortening devices include:

- Saturable absorbers
- Phase modulators
- Dispersion compensators
- Optical-Kerr media

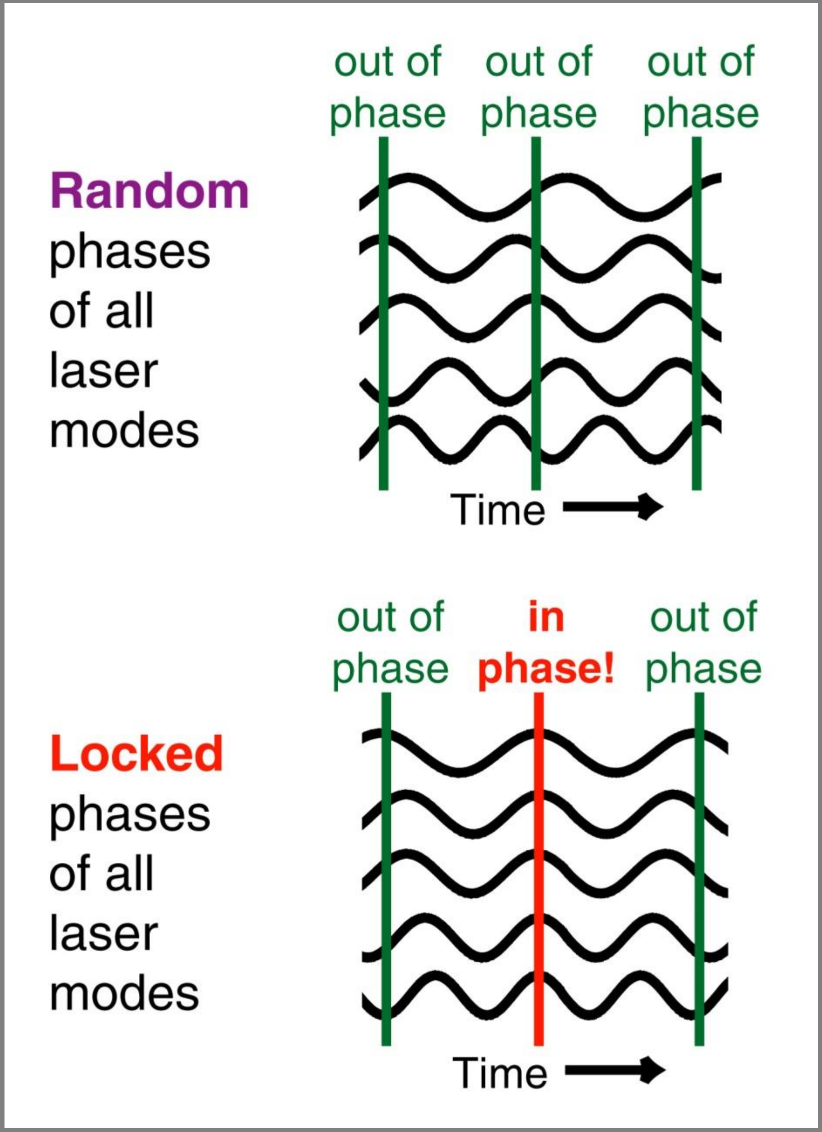
One way to make short pulses: the saturable absorber

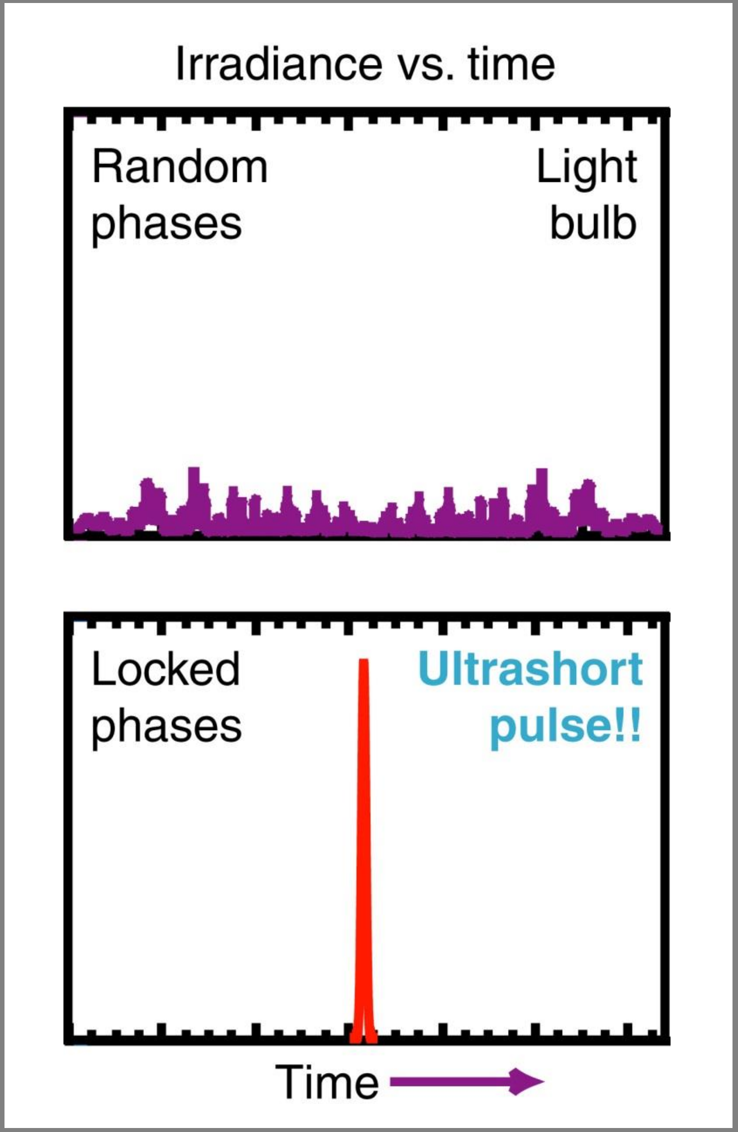


Like a sponge, an absorbing medium can only absorb so much. High-intensity spikes burn through; low-intensity light is absorbed.

Generating short pulses = "mode-locking"

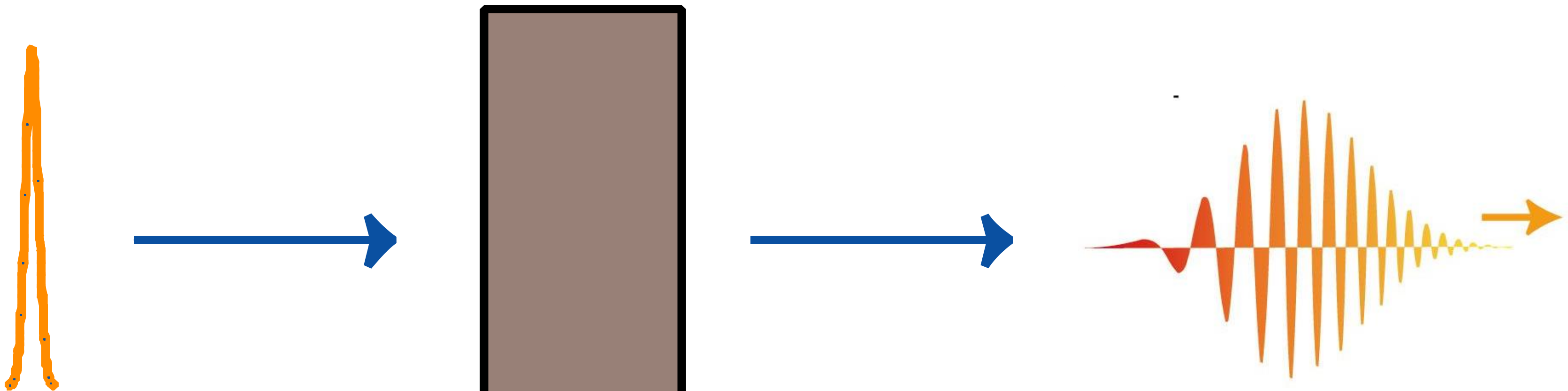
Locking the phases of the laser frequencies yields an ultrashort pulse.





Group velocity dispersion broadens ultrashort laser pulses

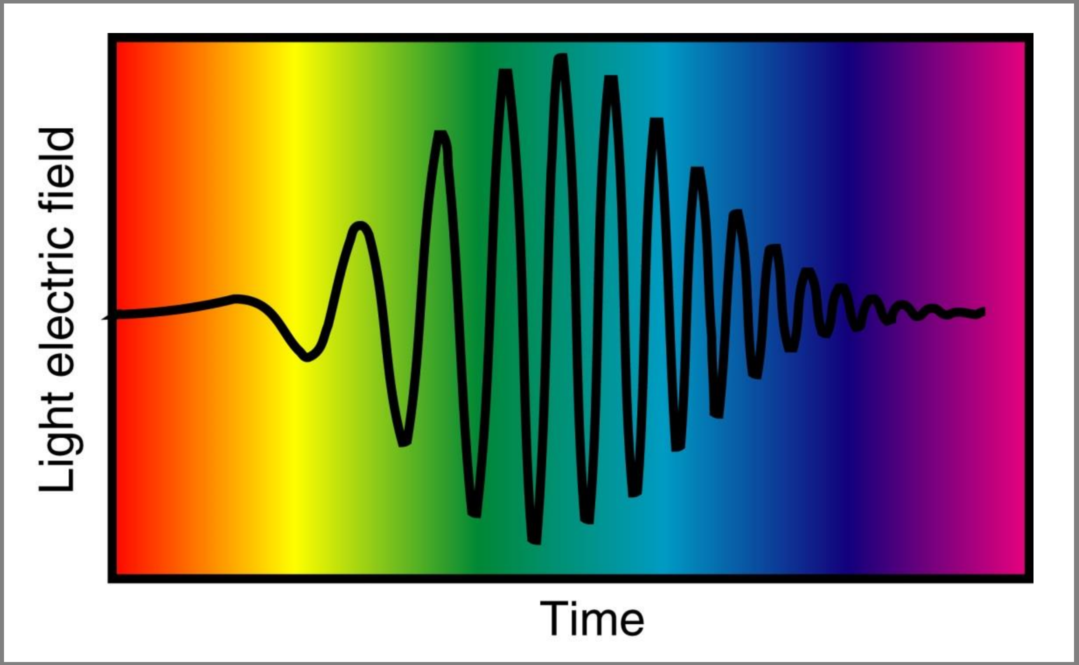
Different frequencies travel at different group velocities in materials, causing pulses to expand to highly "chirped" (frequency-swept) pulses.



Longer wavelengths almost always travel faster than shorter ones.

The Linearly Chirped Pulse

Group velocity dispersion produces a pulse whose frequency varies in time.



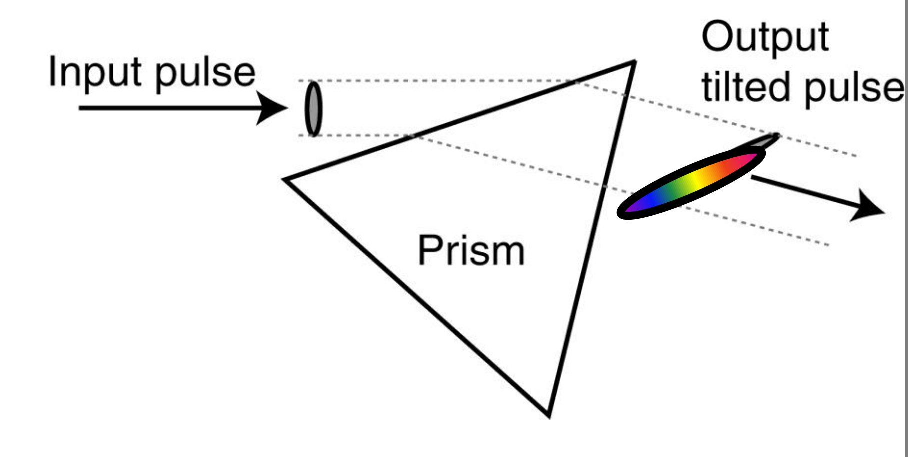
This pulse increases its frequency linearly in time (from red to blue).

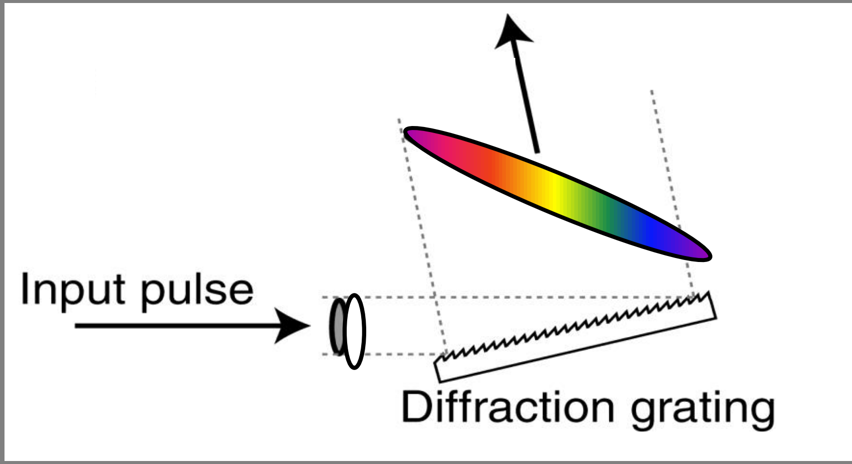
In analogy to bird sounds, this pulse is called a "chirped" pulse.

Dispersion causes pulse fronts to tilt.

Phase fronts are perpendicular to the direction of propagation.

Because the group velocity is usually less than the phase velocity, pulse intensity fronts tilt when light traverses a prism. With gratings, it's a simple light-travel-distance issue.





This effect can be useful (for measuring pulses), but it can also be a pain.

Prisms

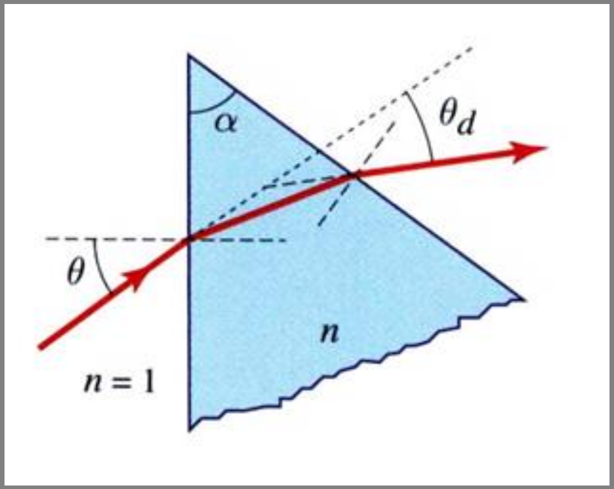
A prism of **apex angle** α and refractive index n deflects a ray incident at an angle θ by an angle:

$$\theta_d = \theta - \alpha + \sin^{-1}\left[\sqrt{n^2 - \sin^2\theta}\,\sin\alpha - \sin\theta\cos\alpha\right]. \qquad (1.2\text{-}6)$$

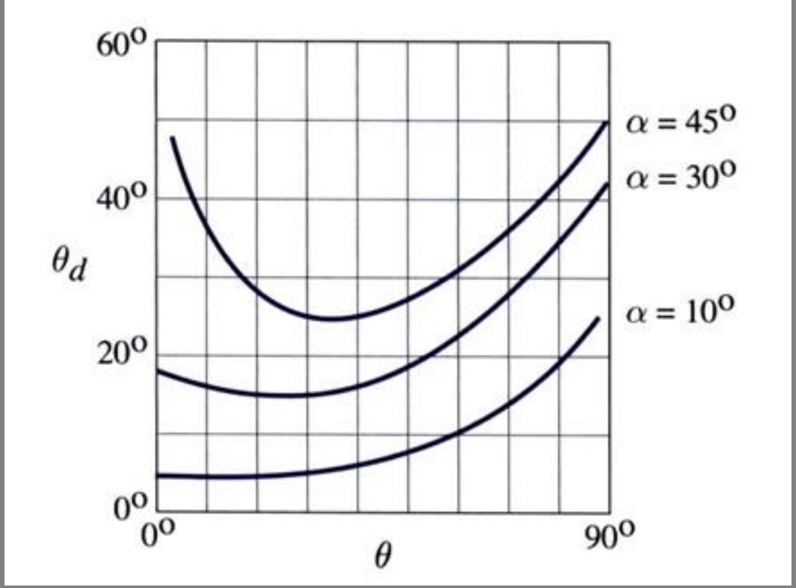
When α and θ are very small

$$\theta_d \approx (n-1)\,\alpha \qquad (1.2-7)$$

Ray deflection by the prism

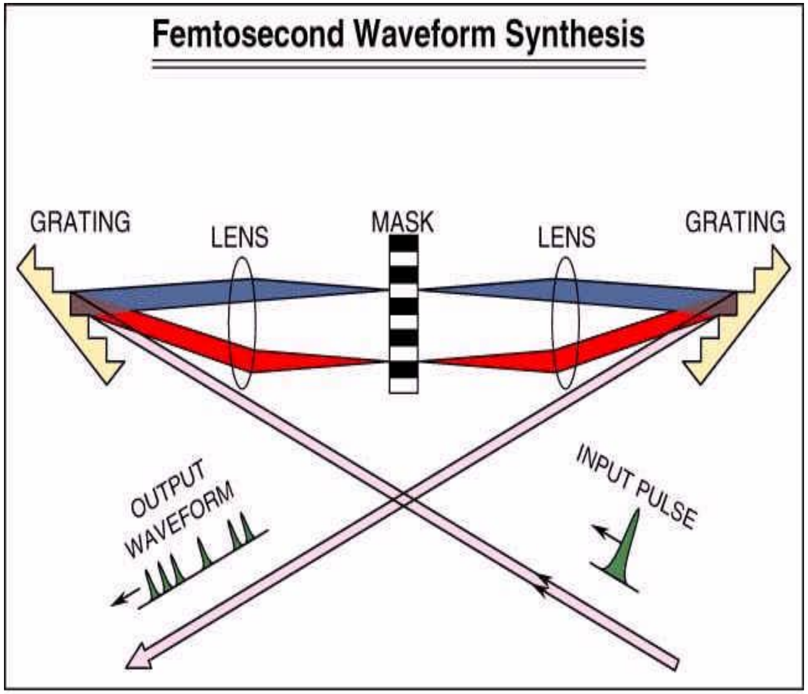


***n* = 1.5**



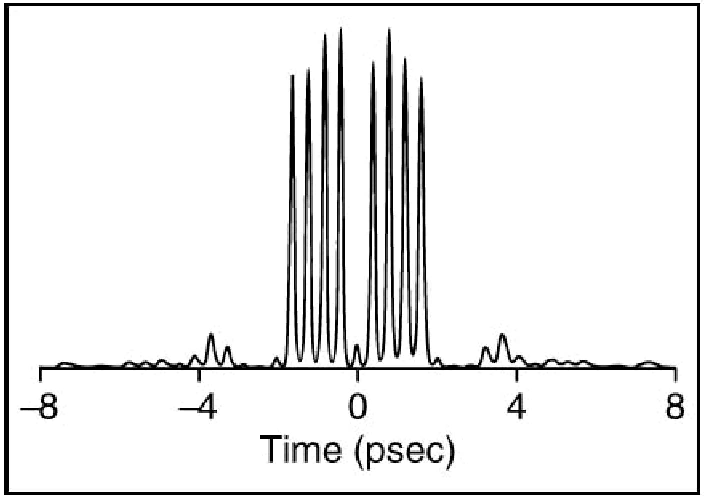
We can shape ultrashort pulses.

This usually occurs in the frequency domain.



Purdue University Ultrafast Optics Group

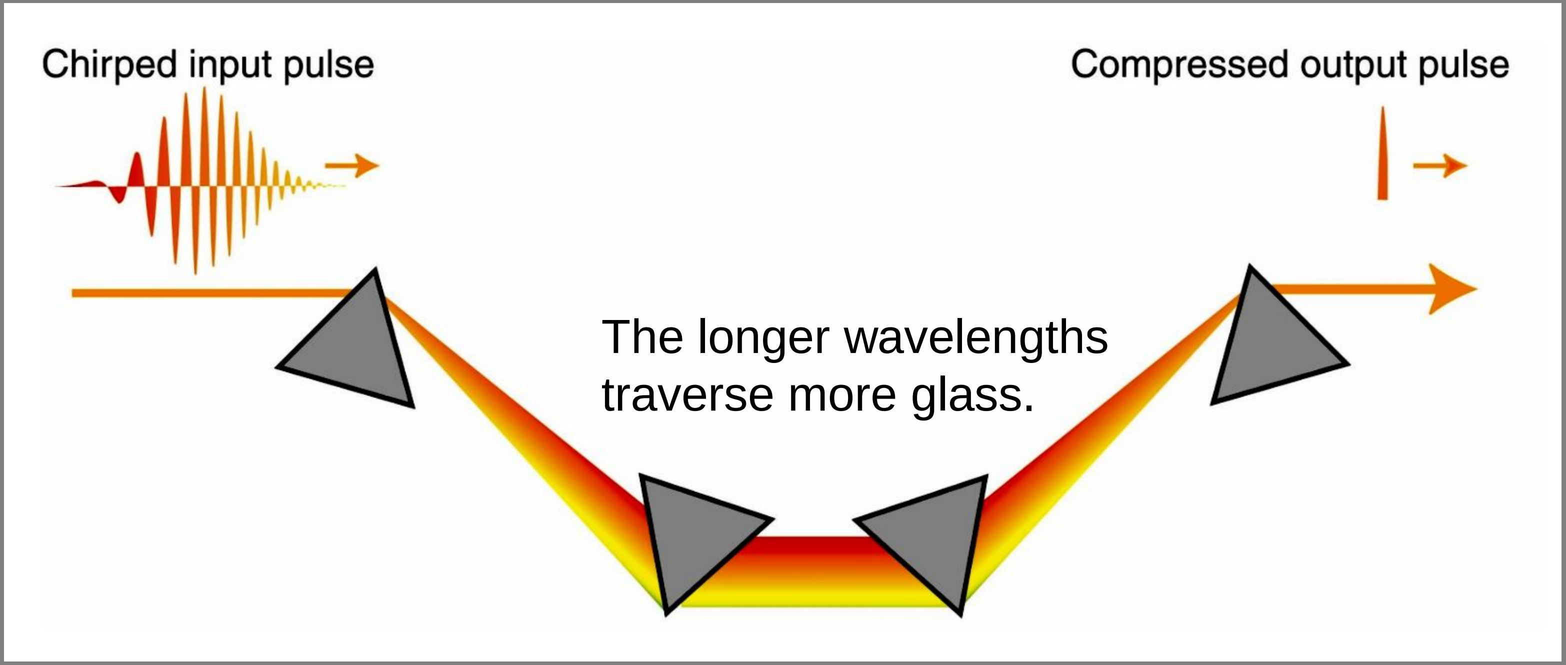
Experimentally measured shaped pulse



Purdue University Ultrafast Optics Group

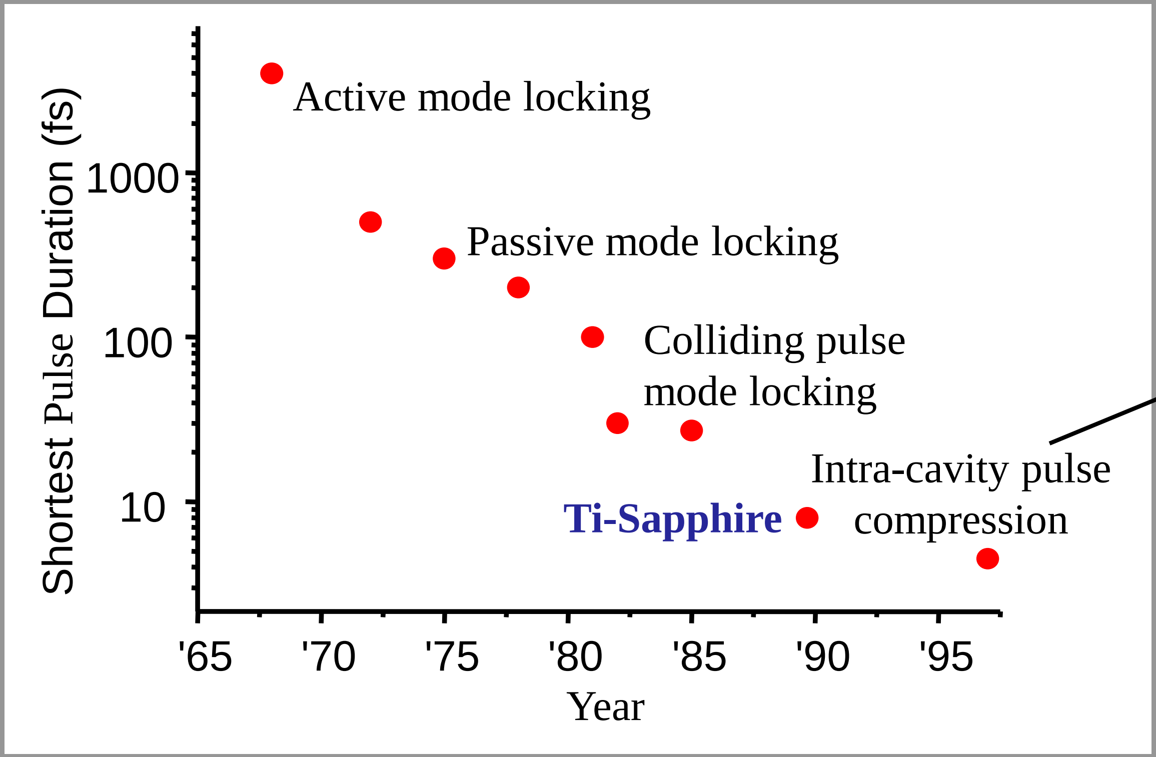
Pulse Compressor

This device has negative group-velocity dispersion and hence can compensate for propagation through materials (i.e., for positive chirp).

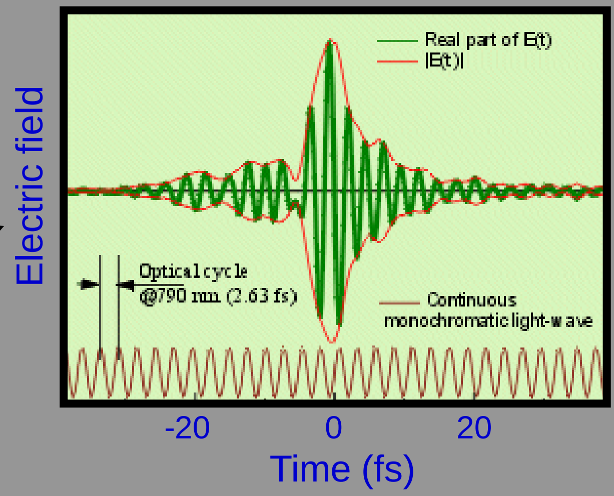


It's routine to stretch and then compress ultrashort pulses by factors of >1000

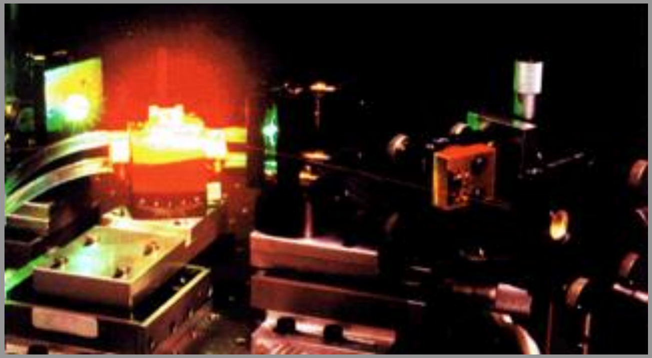
Ultrafast Lasers



The electric field of a 4.5-fs pulse



Ultrafast Ti:sapphire laser

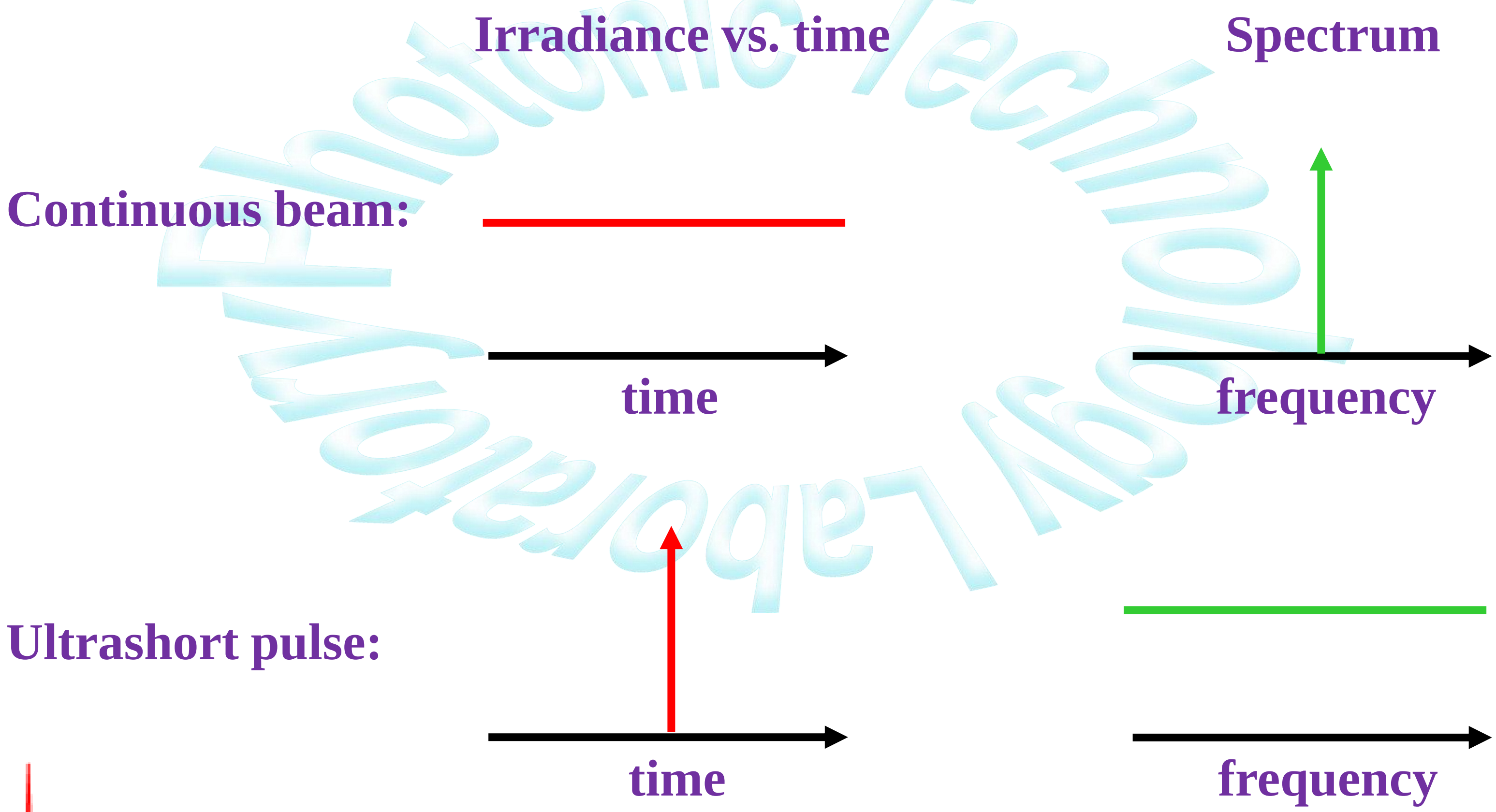


Current record:
4.0 fsec
Baltuska, et al. 2001

Reports of attosecond pulses, too!

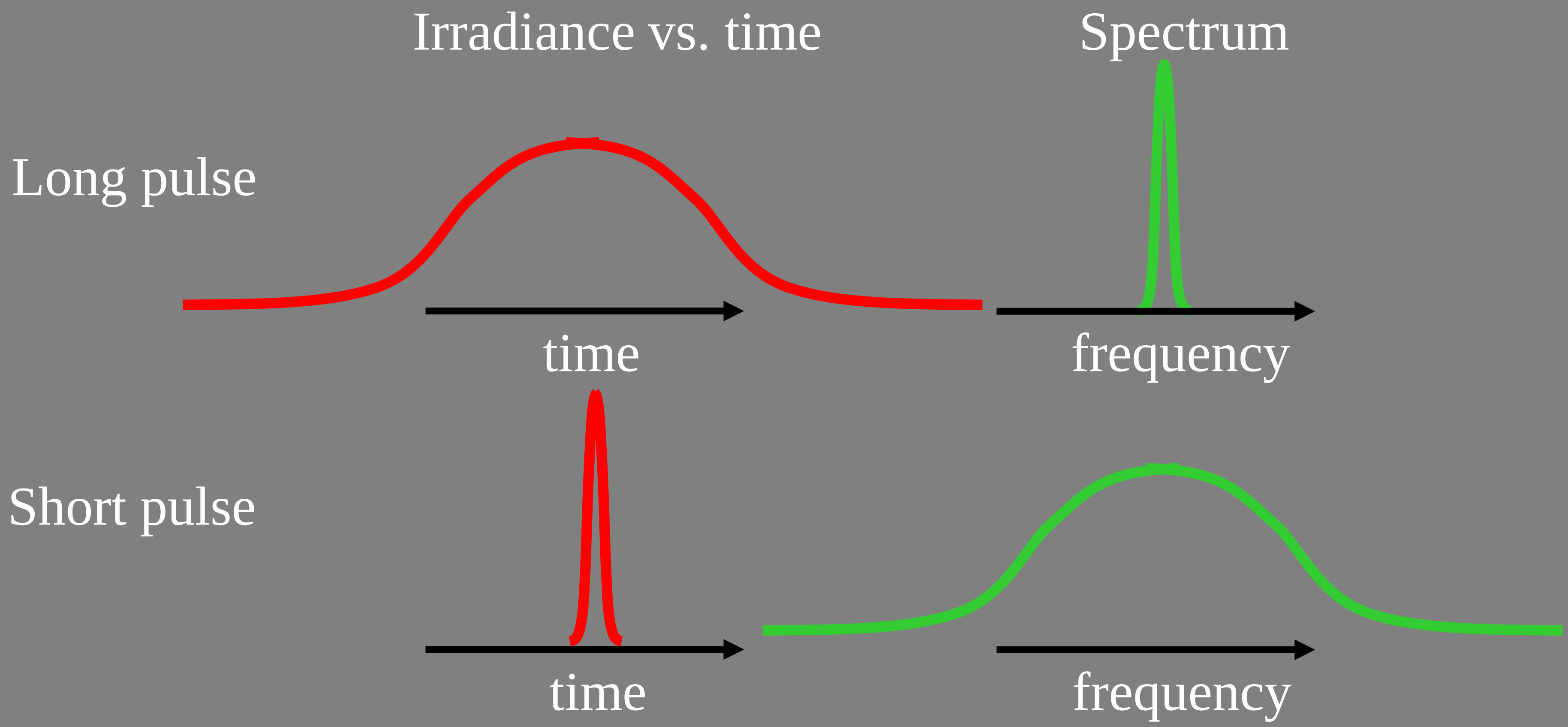
Continuous vs. ultrashort pulses of light

A constant and a delta-function are a Fourier-Transform pair.



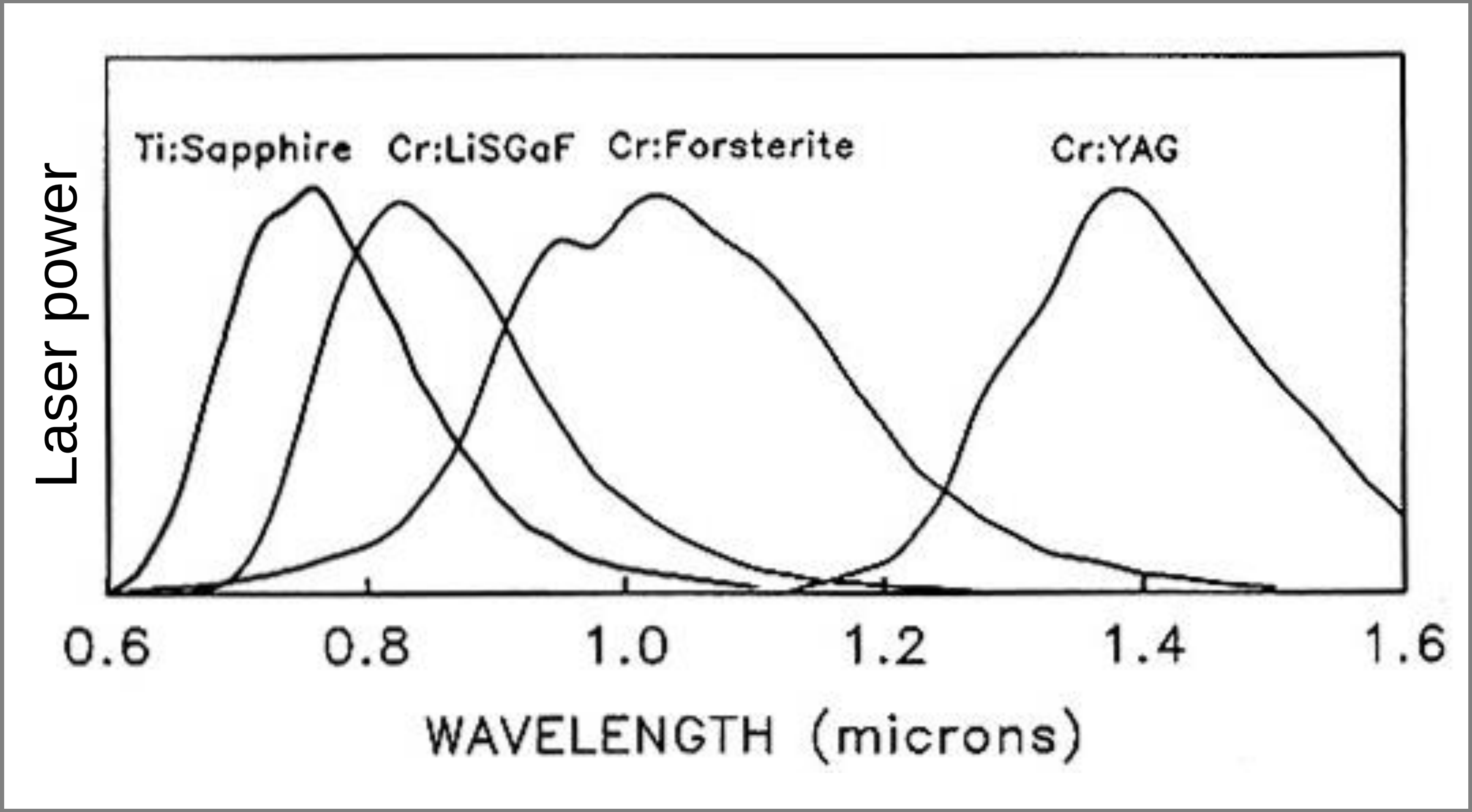
Long vs. short pulses of light

The uncertainty principle says that the product of the temporal and spectral pulse widths is greater than ~1.



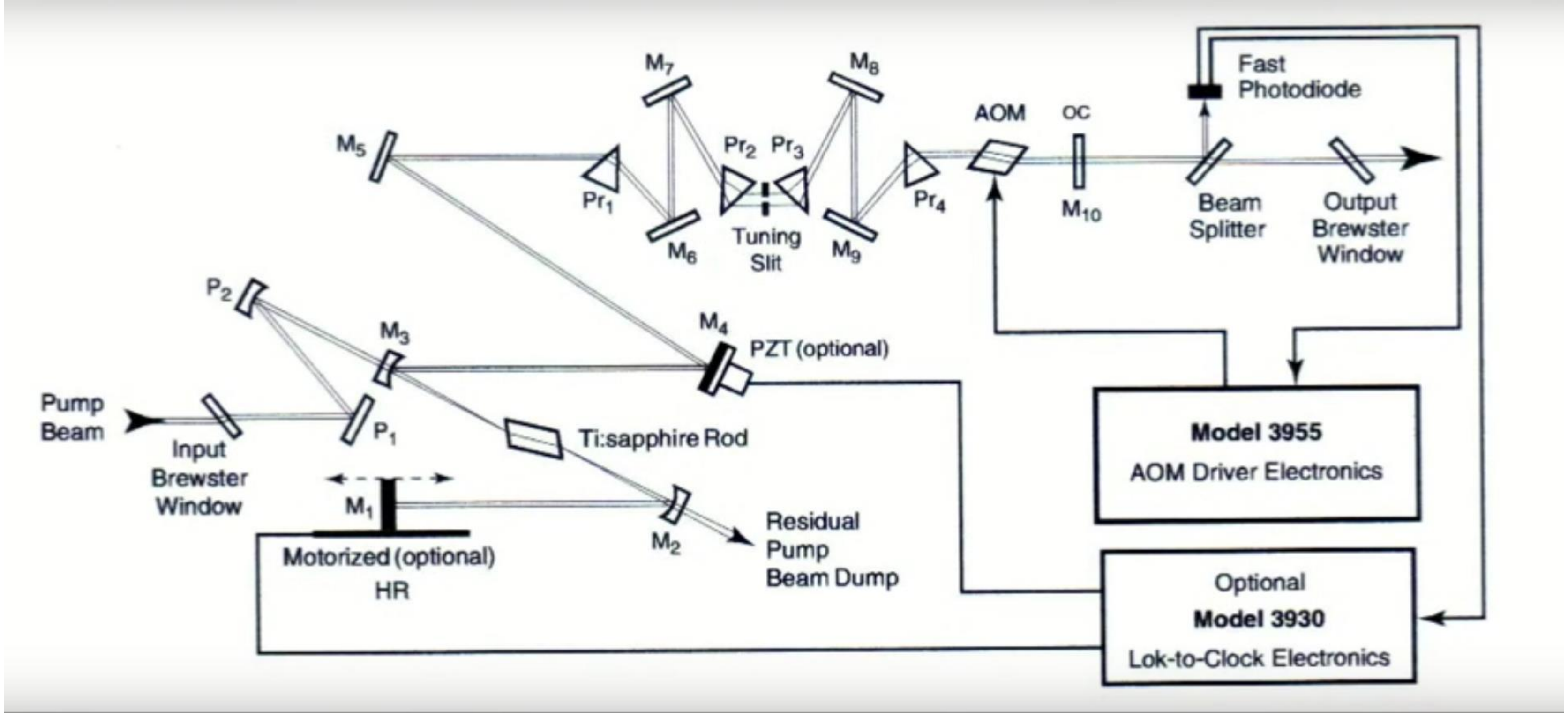
Ultrafast laser media

Solid-state laser media have broad bandwidths and are convenient.



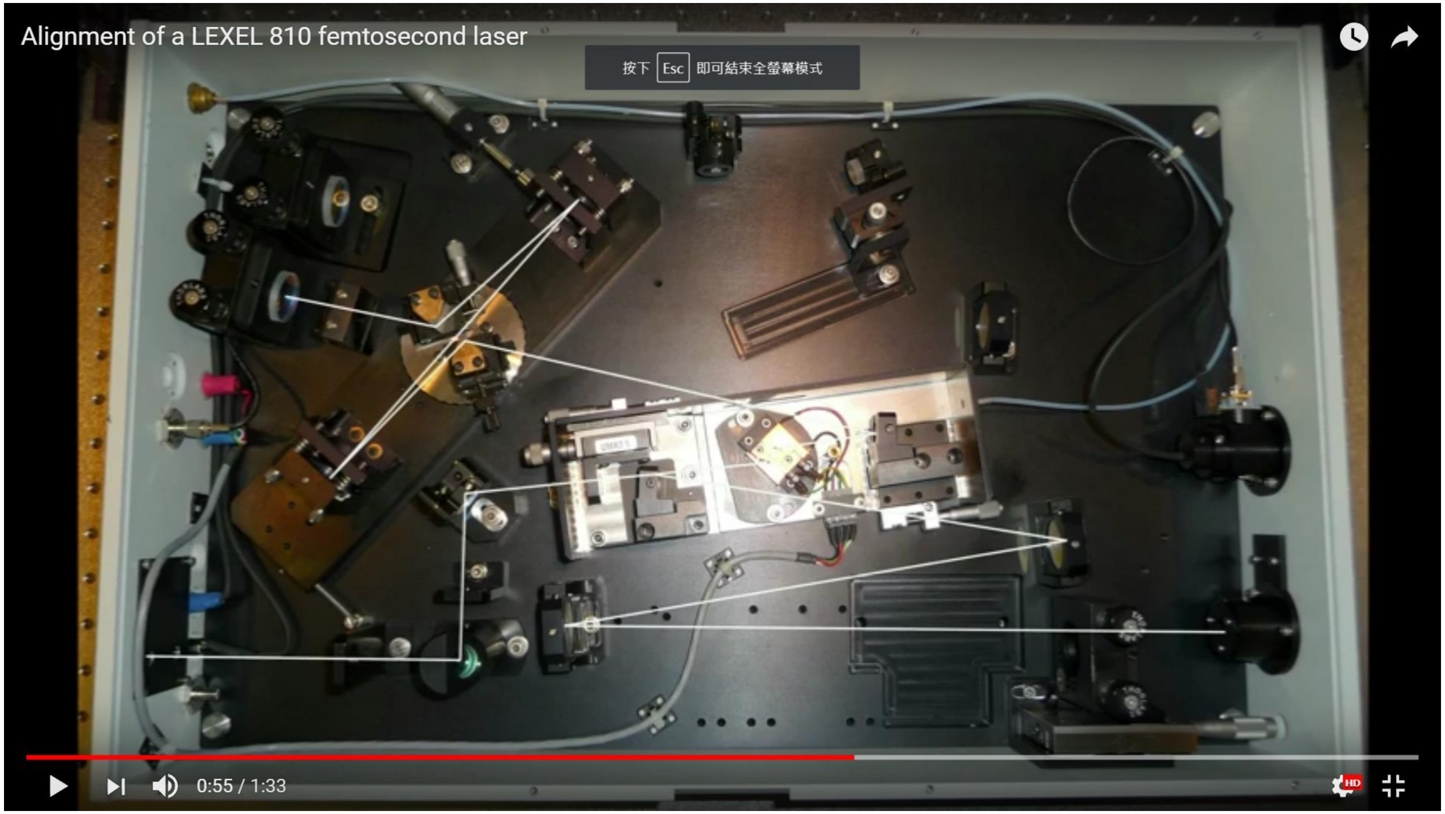
Mode locked fs Ti:sapphire laser

- https://www.youtube.com/watch?v=KX6h9CVXYkA



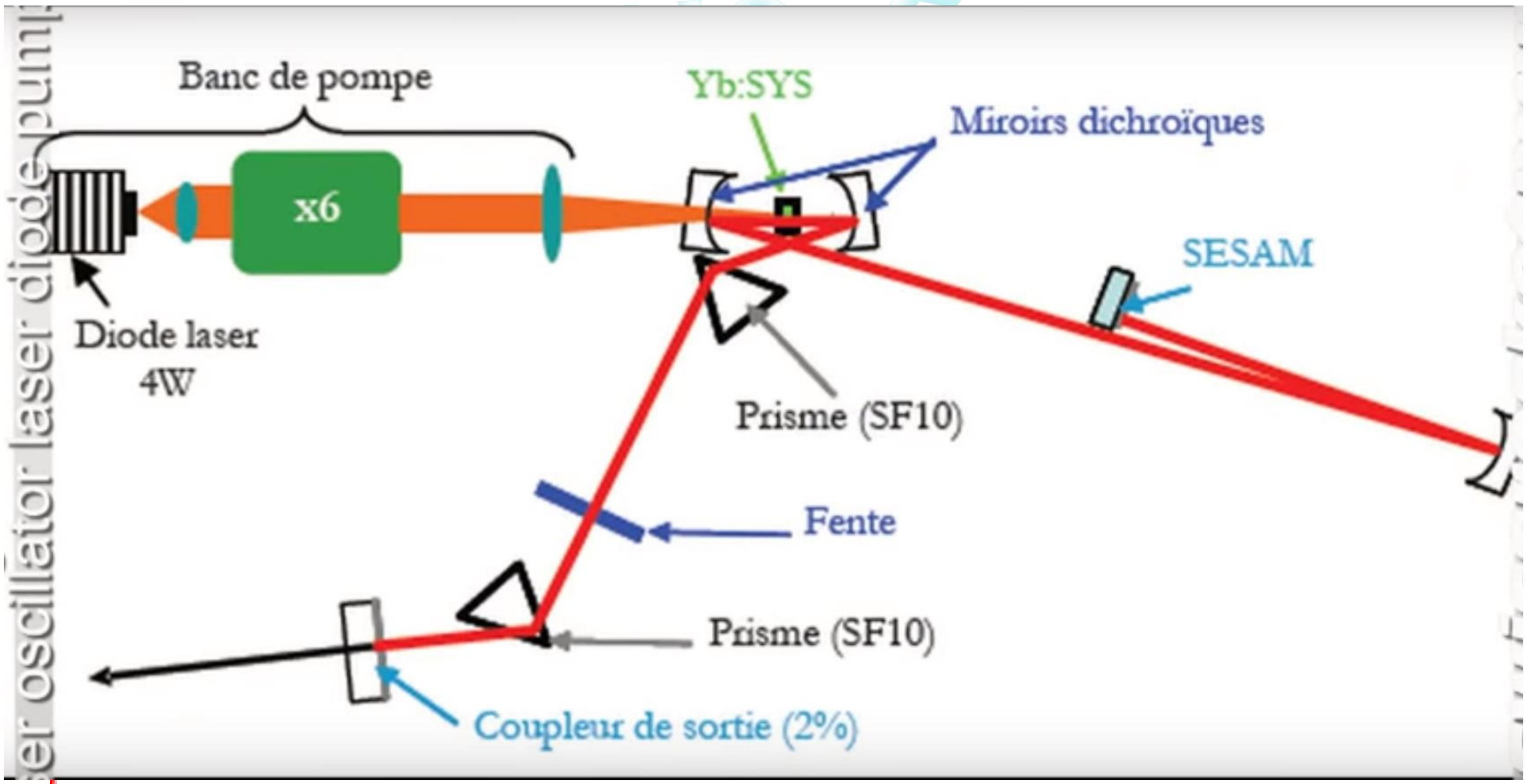
fs Ti:sapphire laser

- https://www.youtube.com/watch?v=1ASzzqeQOzc



fs laser pump by a laser diode

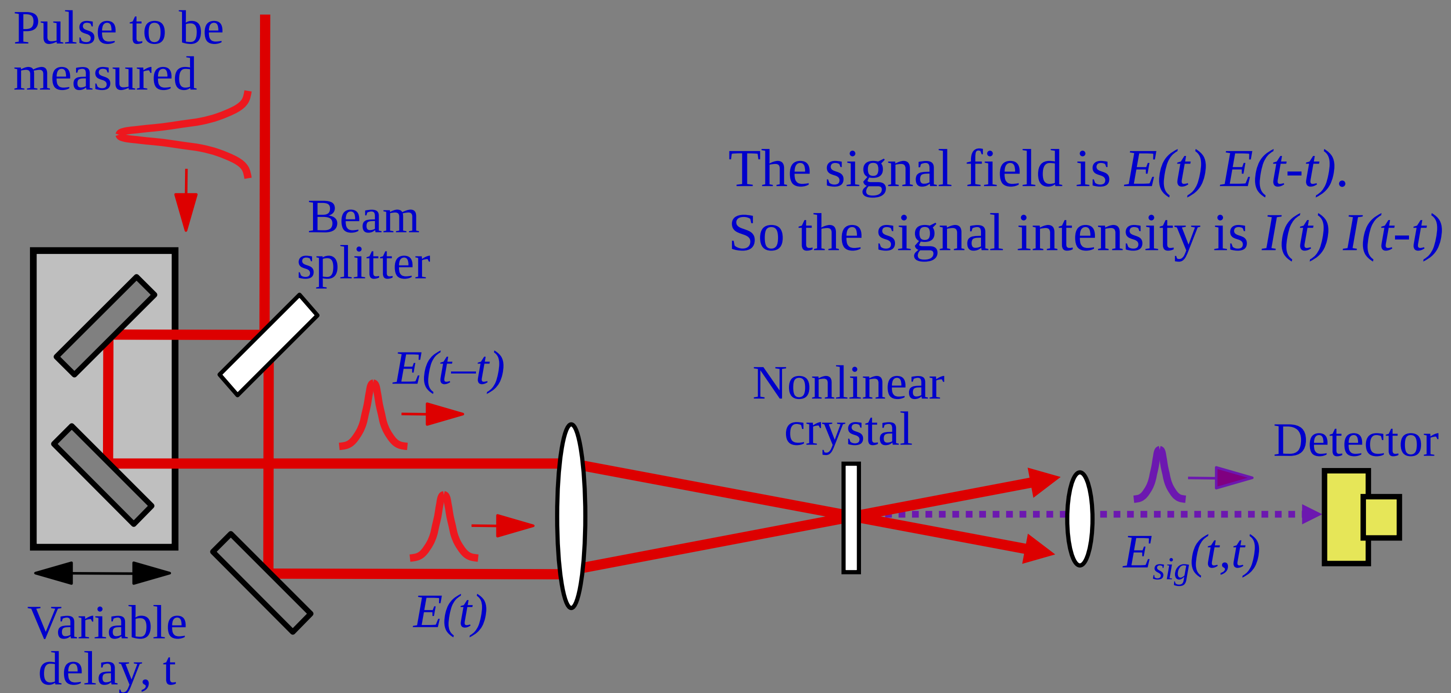
- https://www.youtube.com/watch?v=l62aDMONhf0&t=89s



Using the pulse to measure itself: The Intensity Autocorrelator

Crossing beams in a nonlinear-optical crystal, varying the delay between them, and measuring the signal pulse energy vs. delay, yields the **Intensity Autocorrelation, $A^{(2)}(t)$**.

The signal field is *E(t) E(t-t)*.
So the signal intensity is *I(t) I(t-t)*

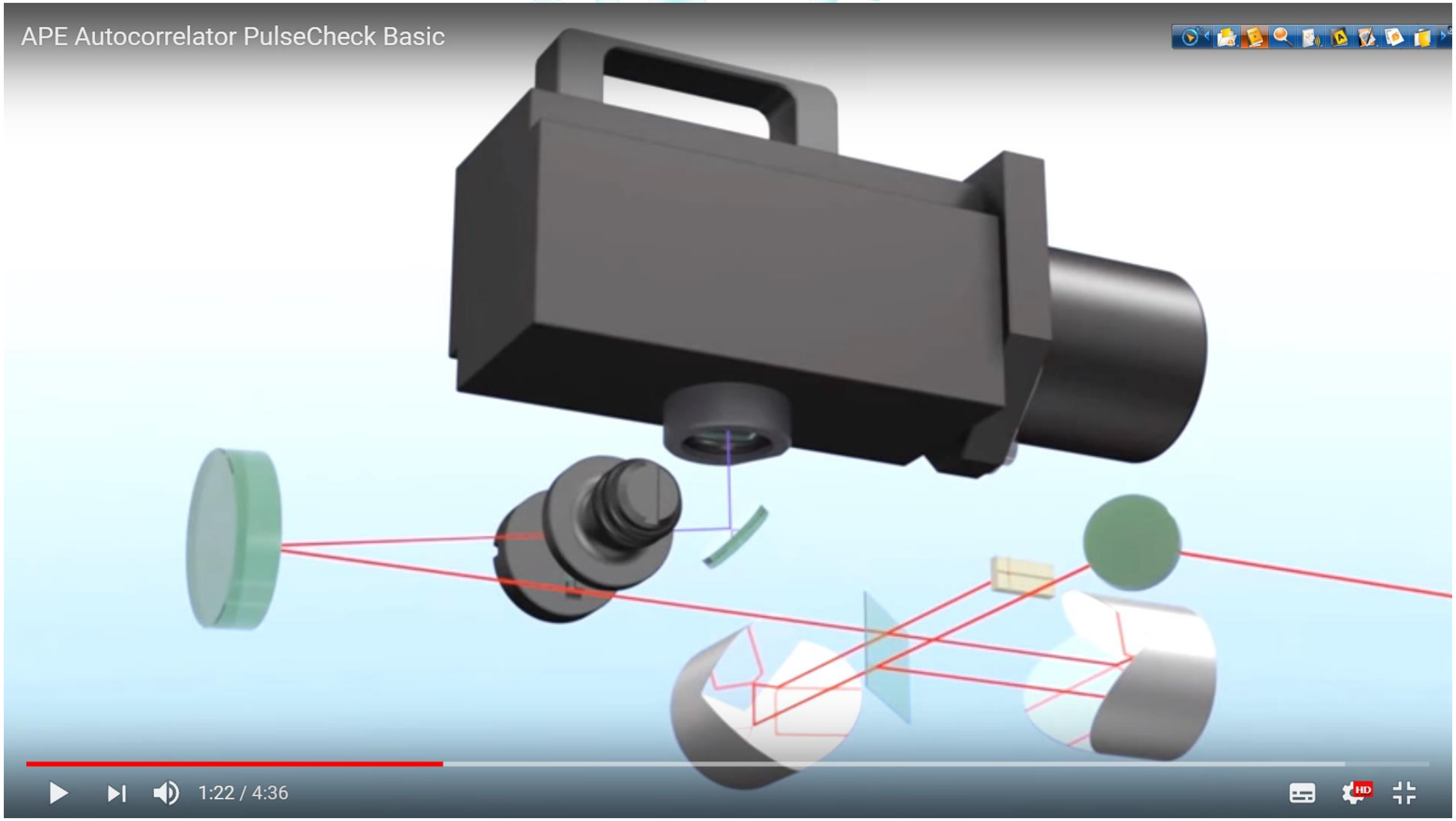


The Intensity Autoco

$$A^{(2)}(\tau) \equiv \int_{-\infty}^{\infty} I(t) I(t-\tau) dt$$

Autocorrelator

- https://www.youtube.com/watch?v=J1pNHYySSYg

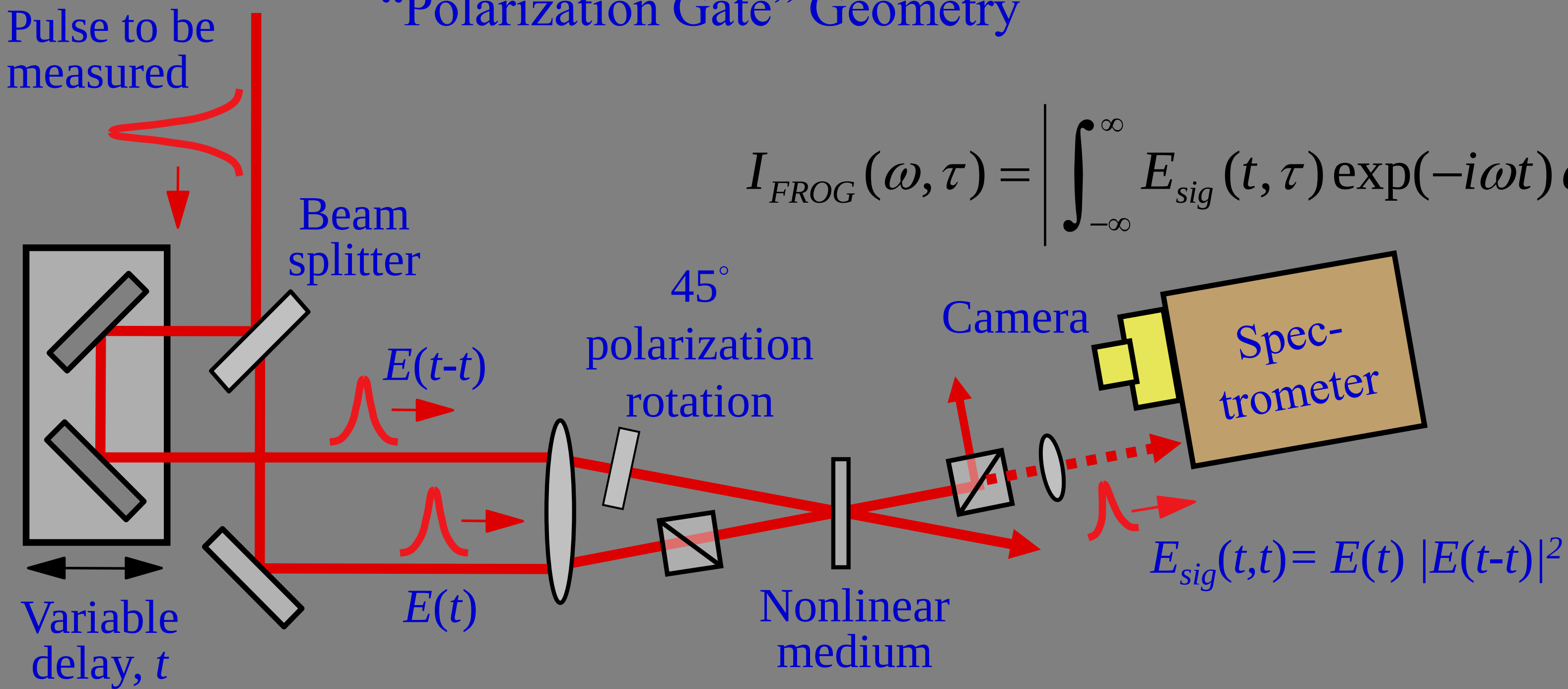


Frequency-Resolved Optical Gating (FROG)

FROG involves gating the pulse with a variably delayed replica of itself in an instantaneous nonlinear-optical medium and then spectrally resolving the gated pulse vs. delay.

"Polarization Gate" Geometry

$$I_{FROG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)\,dt \right|^2$$



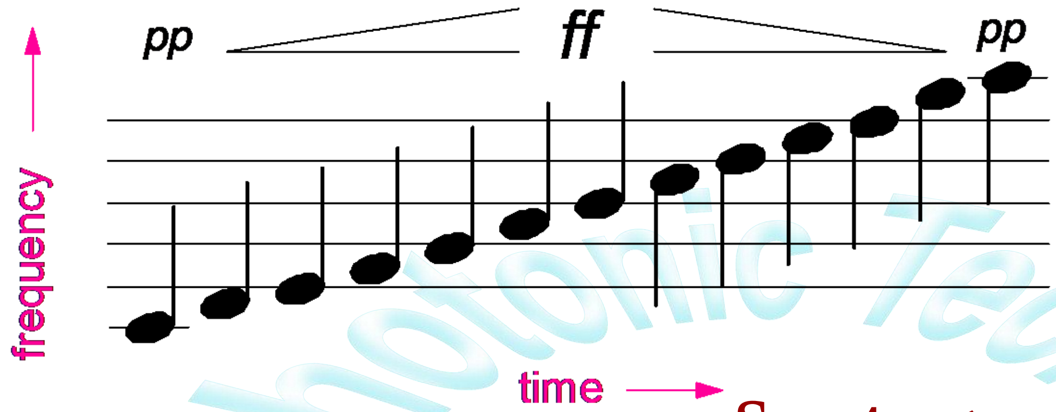
Use any ultrafast nonlinearity: Second-harmonic generation, etc.

R. Trebino, *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses*, Kluwer

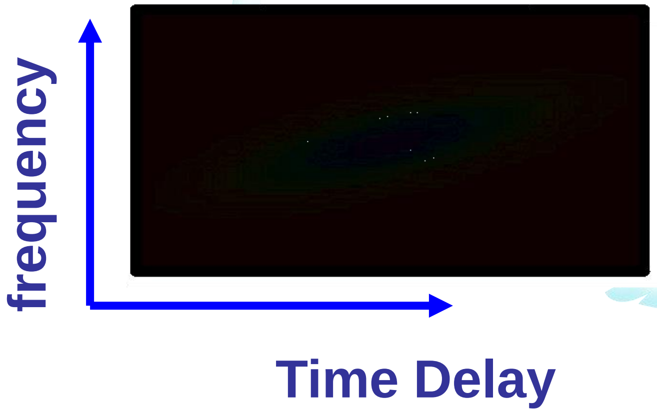
Frequency resolved optical gating (FROG)

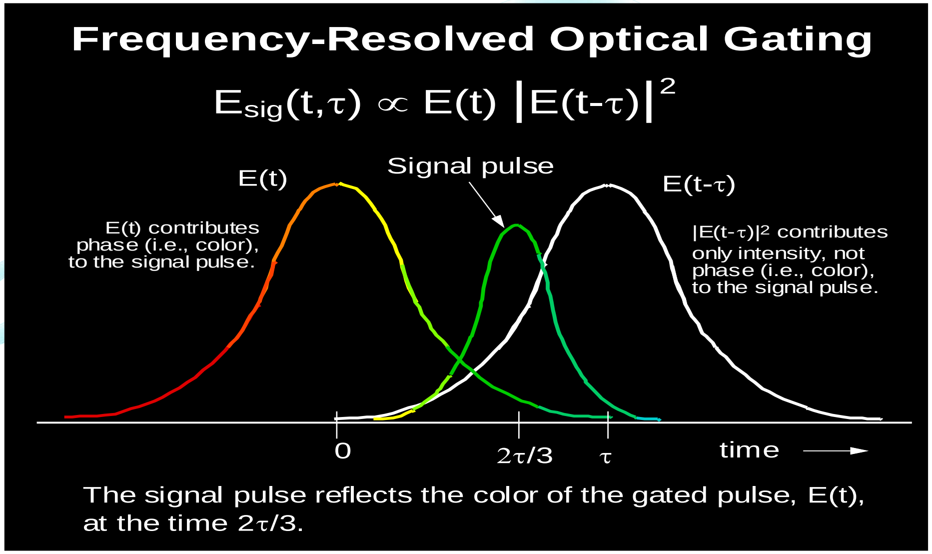
Spectrogram

- Intensity
- Time delay
- Frequency



Spectrogram of E (t)

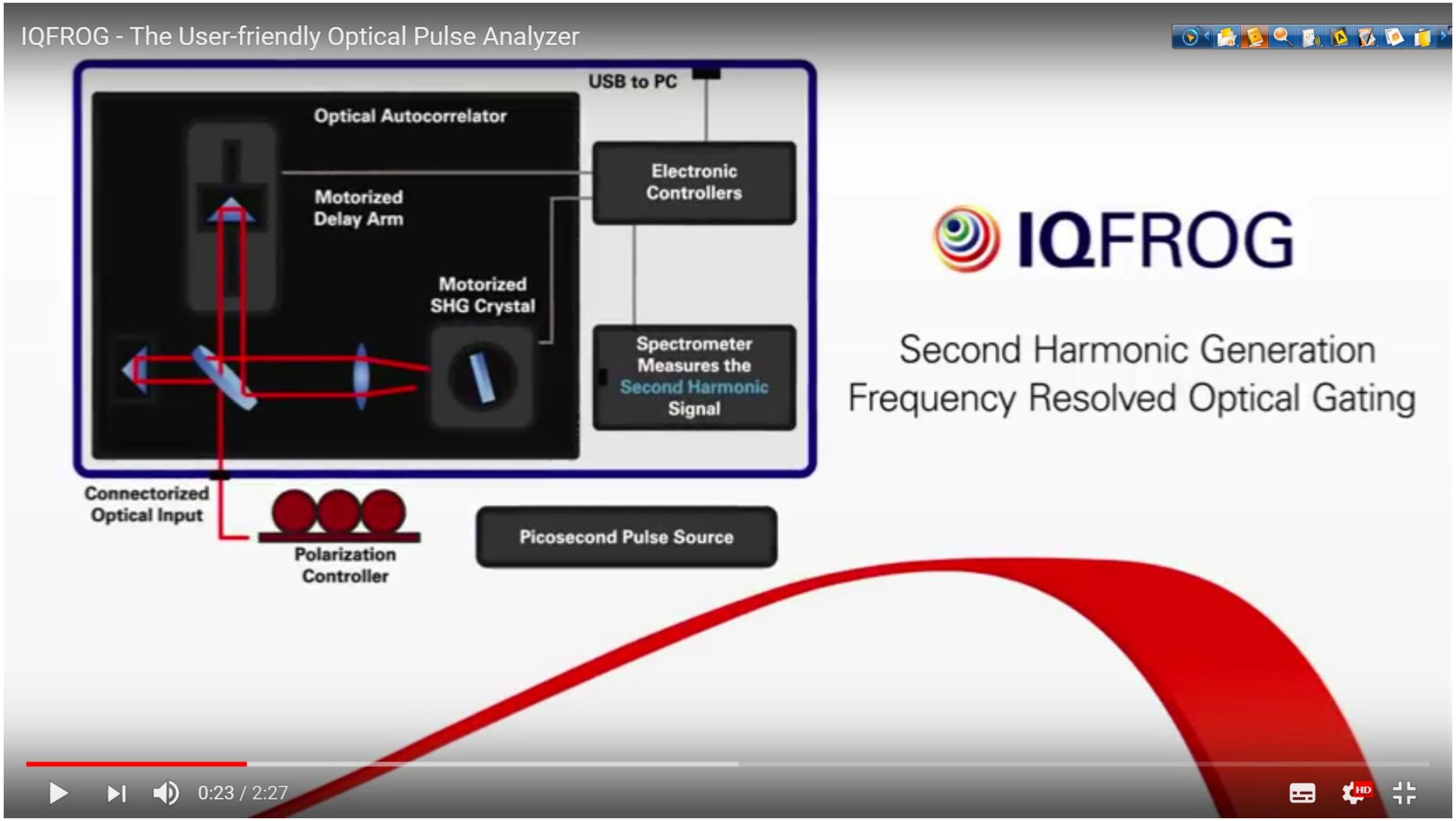




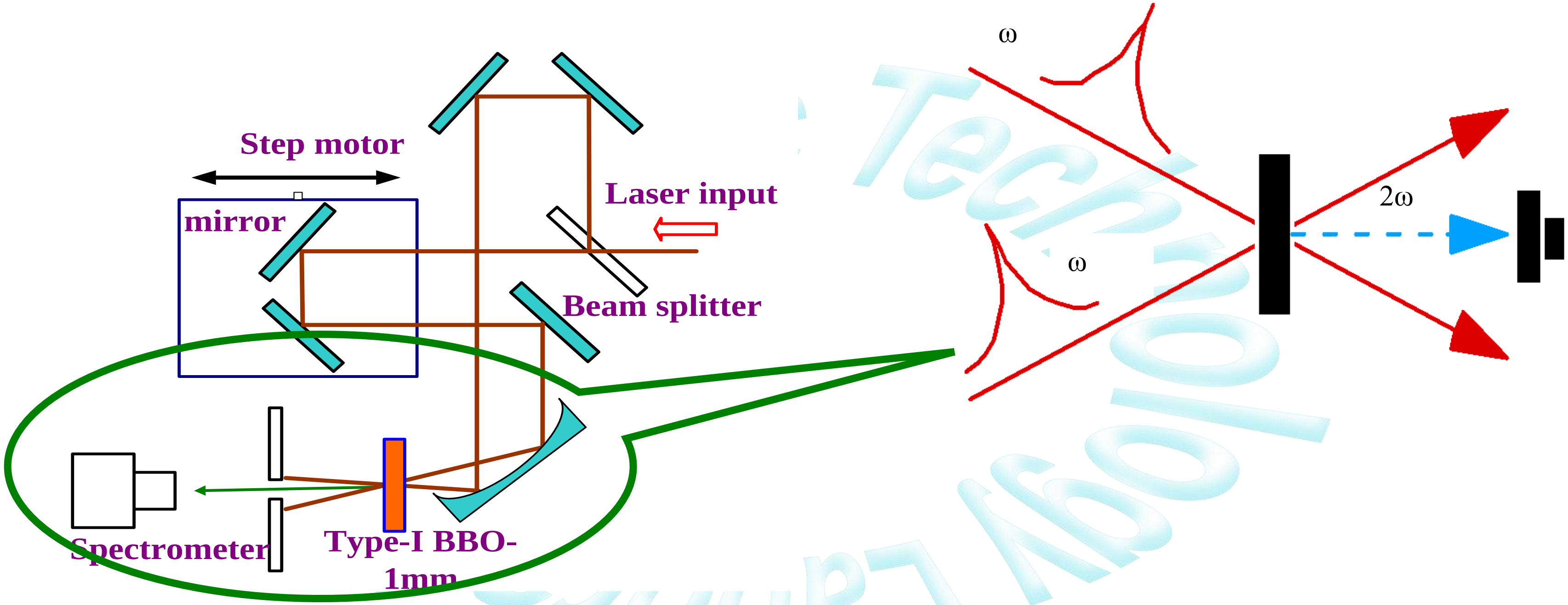
Spectrogram tells us the intensity and color @ time delay

Frog

- https://www.youtube.com/watch?v=lg5sZYFuKNE



Second Harmonic generation FROG

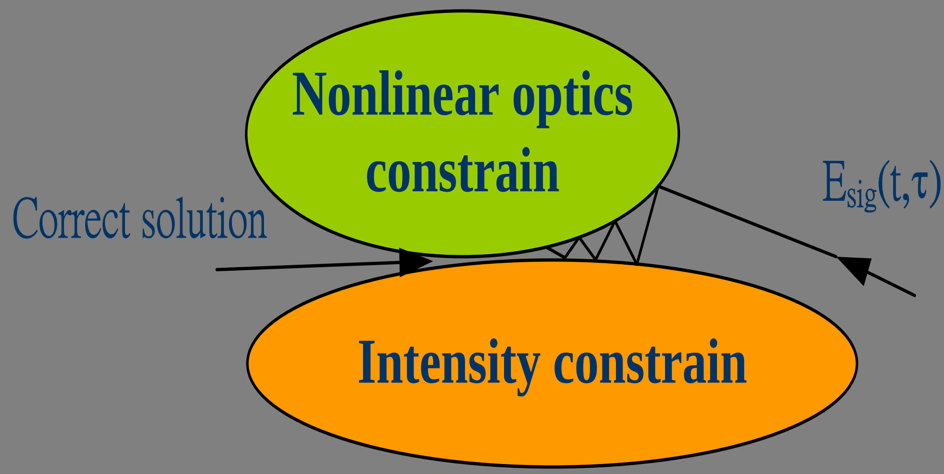


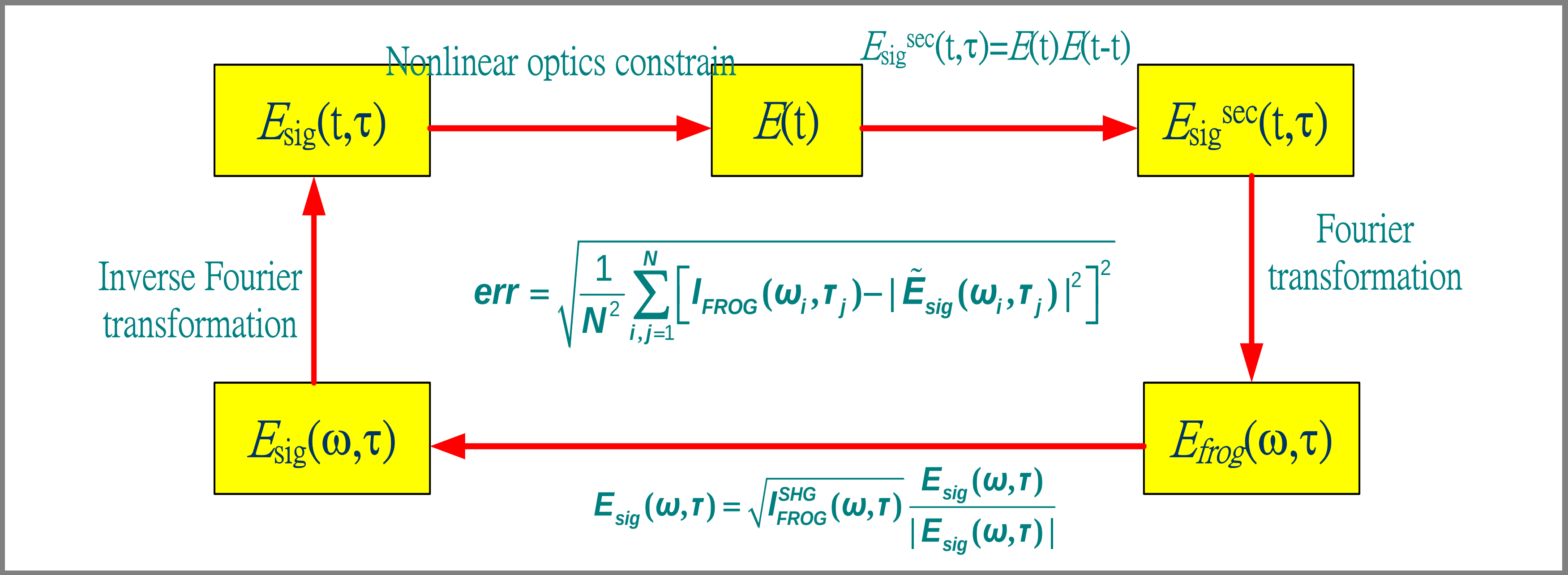
$$I_{FROG}(\omega,\tau) = |\tilde{E}(\omega,\tau)|^2 = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau) e^{i\omega t} dt \right|^2$$

and

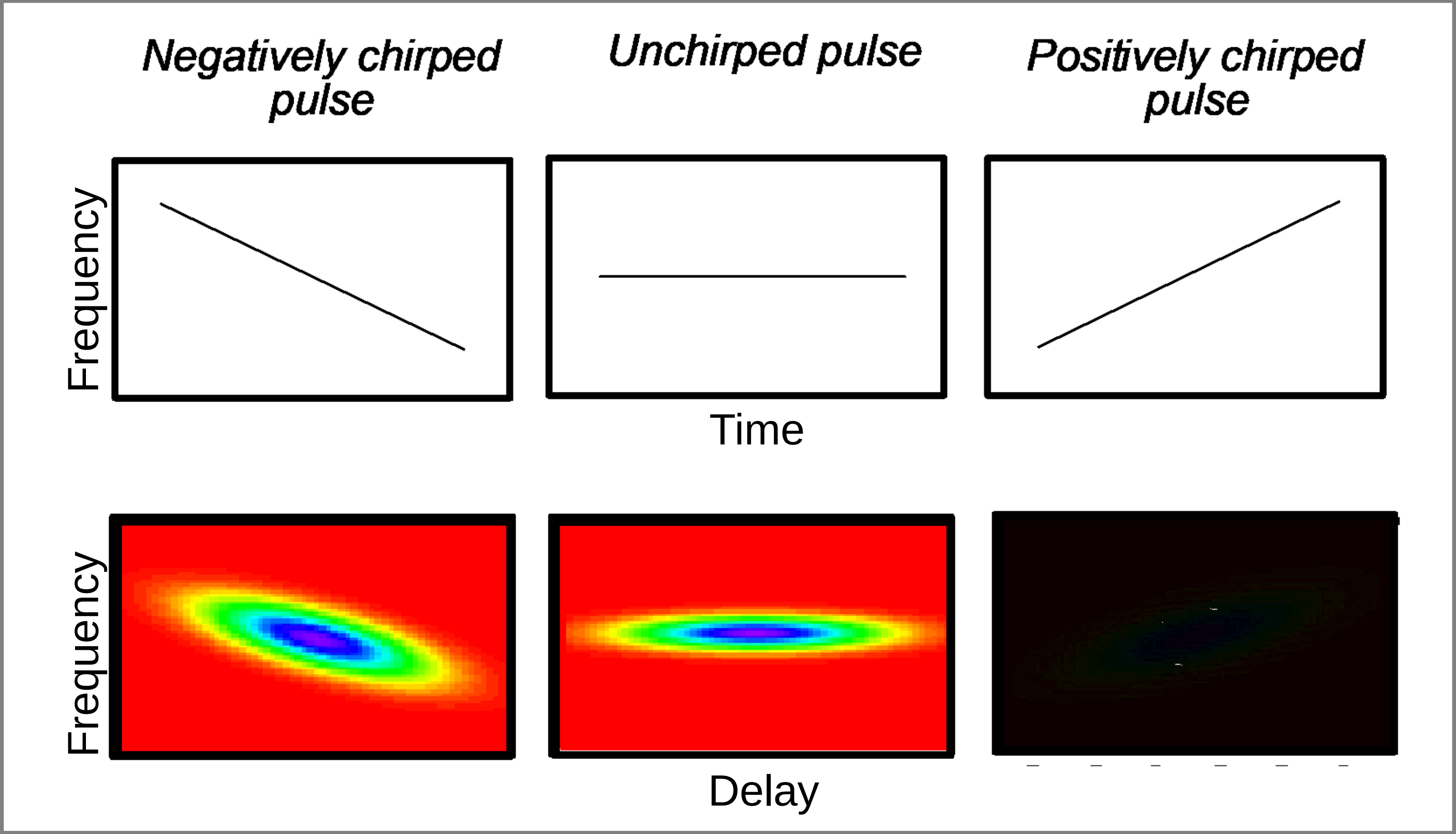
$$E_{sig}(t,\tau) = E(t)G(t-\tau) = E(t)E(t-\tau)$$

Generalized projection



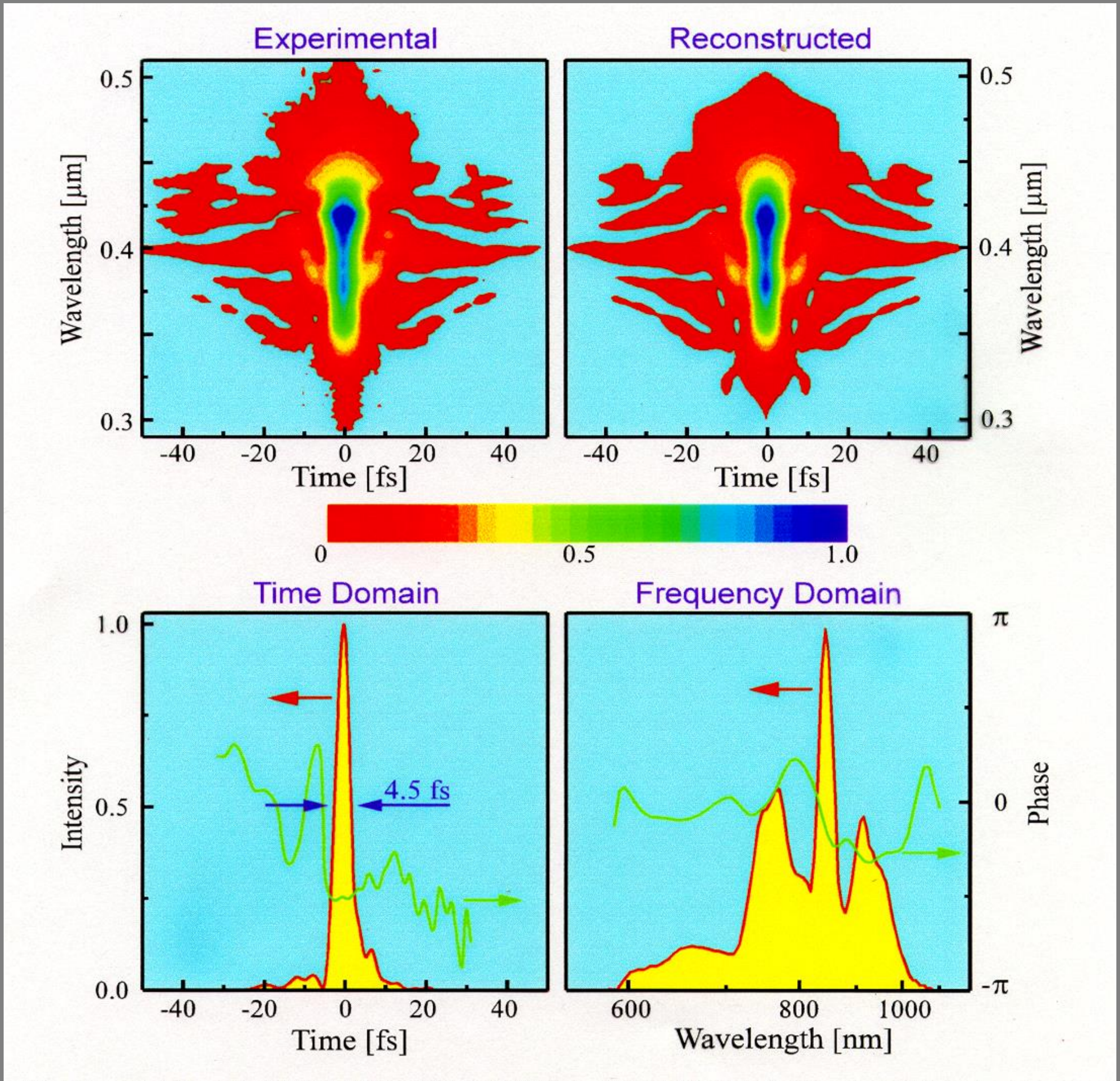


FROG Traces for Linearly Chirped Pulses



The FROG trace visually displays the frequency vs. time.

One of the shortest events ever created!



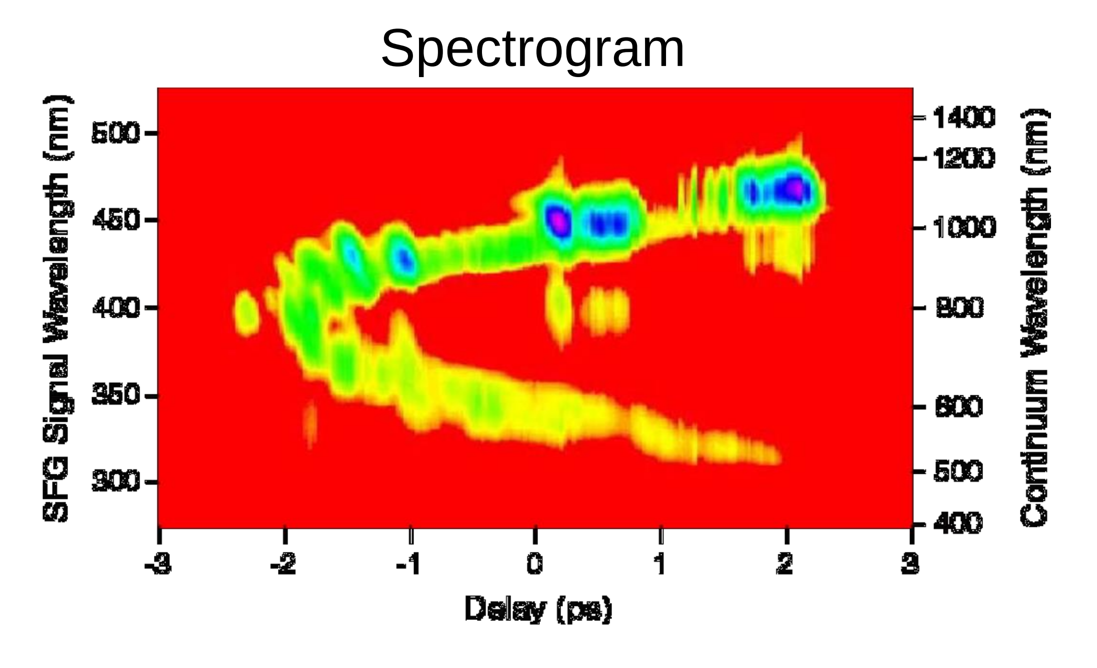
FROG traces

A 4.5 fs pulse!

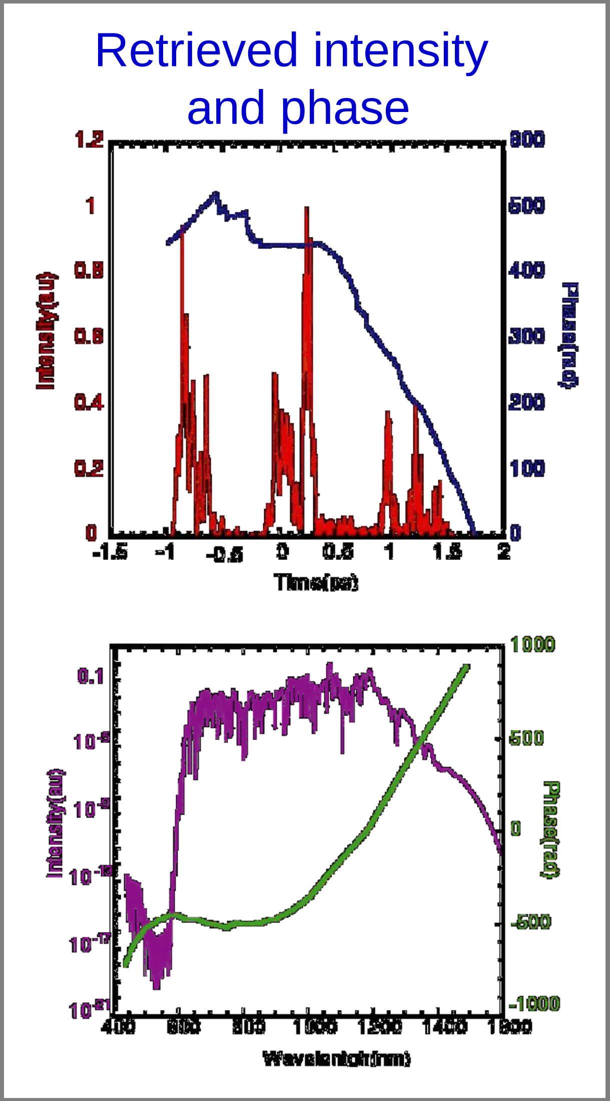
Baltuska,
Pshenichnikov,
and Weirsma,
J. Quant. Electron.,
35, 459 (1999).

FROG Measurement of the Ultrabroadband Continuum

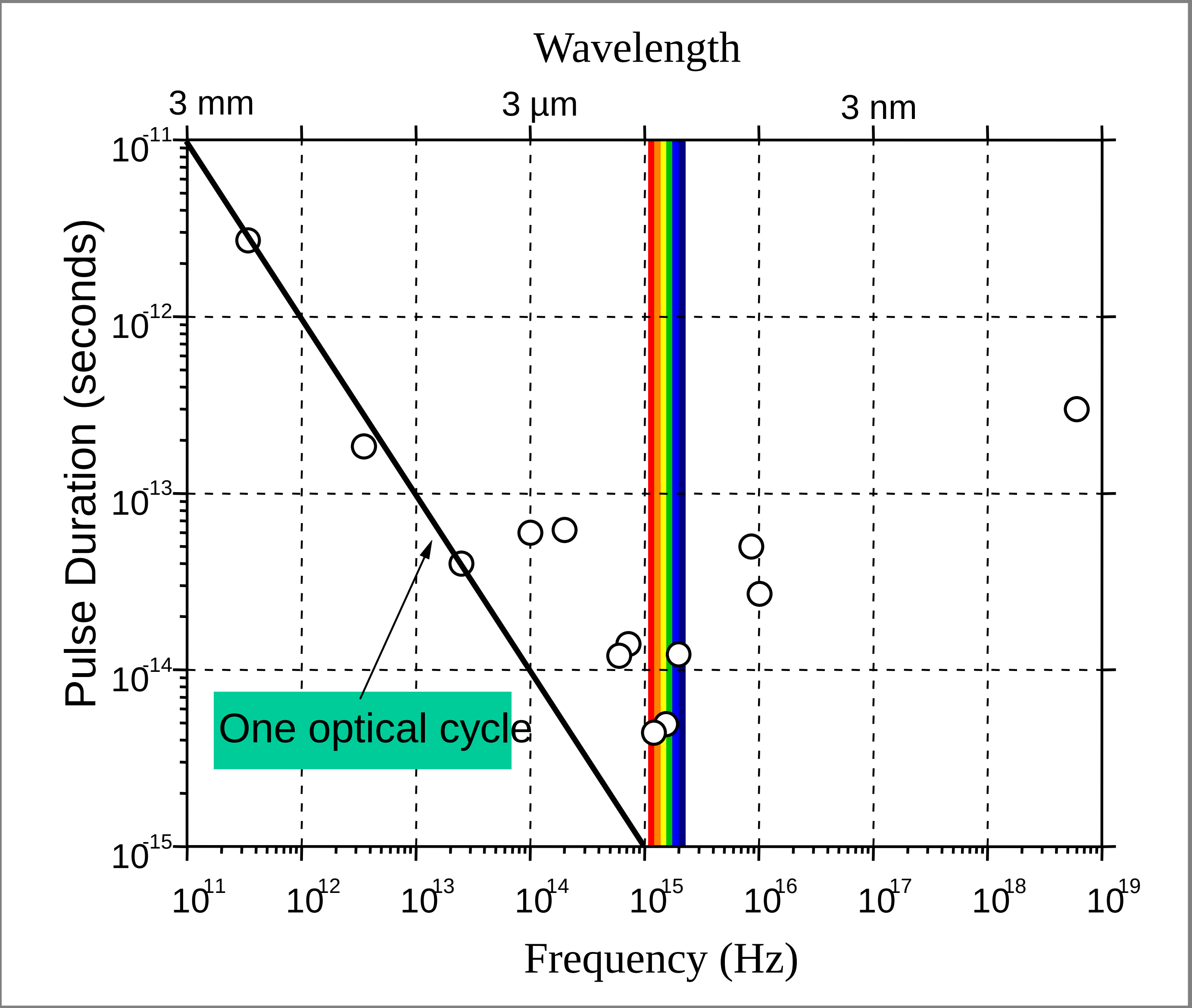
Ultrabroadband continuum was created by propagating 1-nJ, 800-nm, 30-fs pulses through 16 cm of Lucent microstructure fiber.



This pulse has a time-bandwidth product of ~ 4000, and is the most complex ultrashort pulse ever measured.

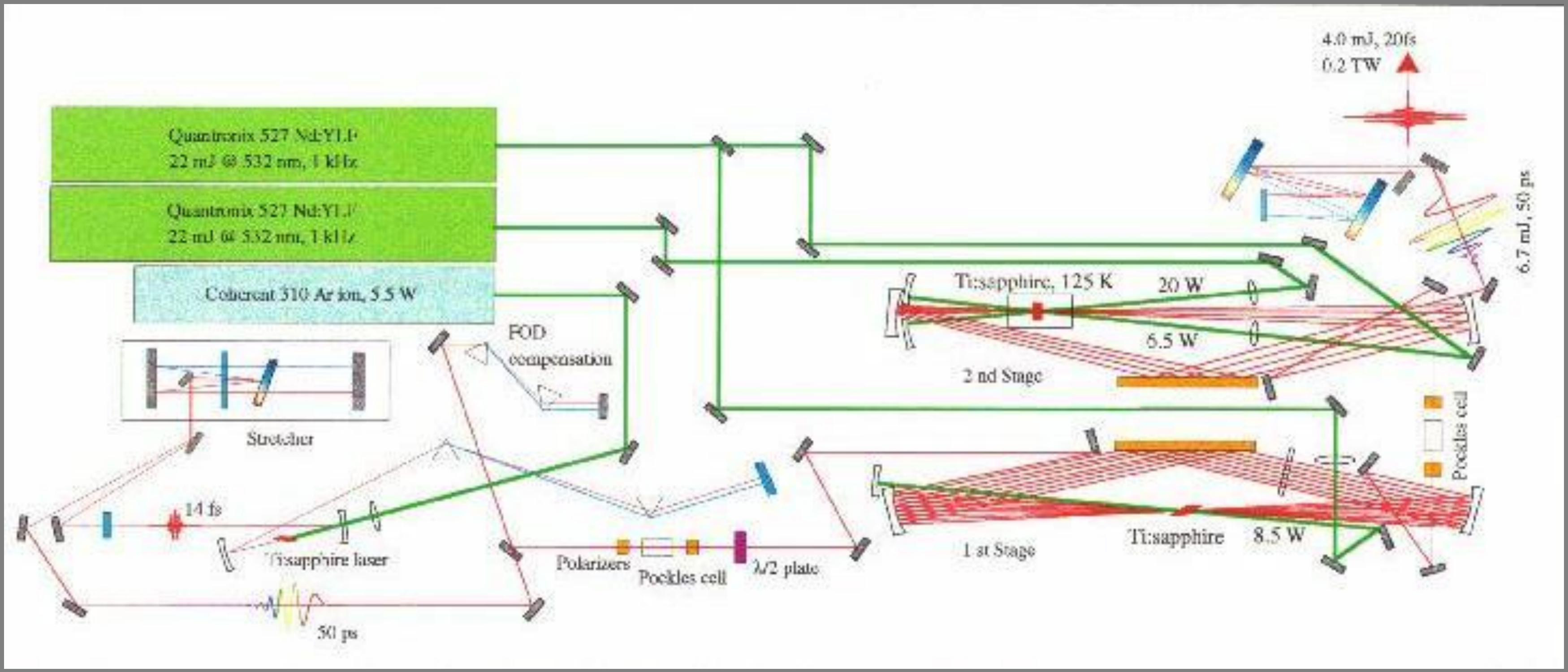


The Shortest Pulses at Different Wavelengths



The Highest Intensities Imaginable

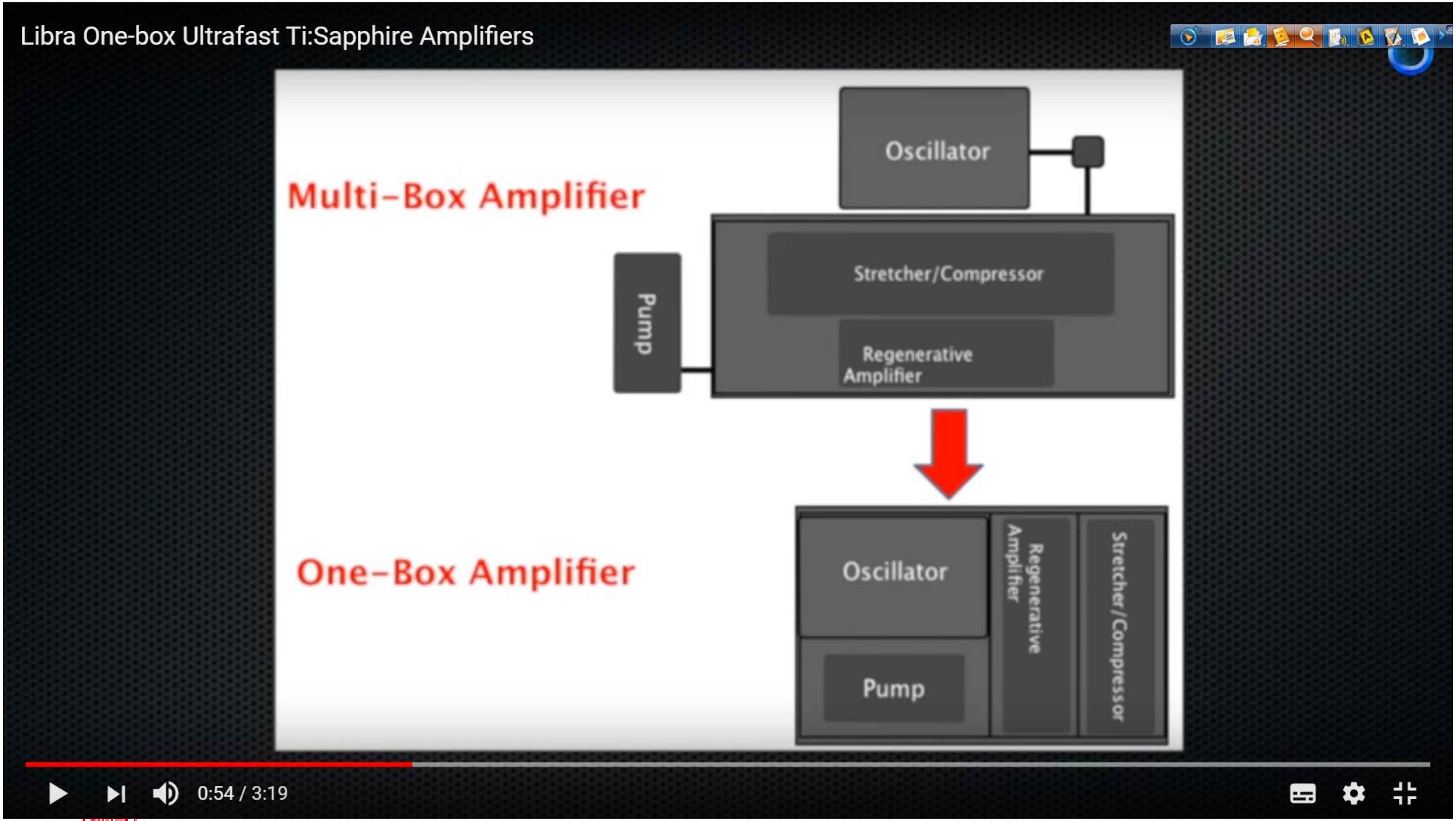
0.2 TW = 200,000,000,000 watts!



1 kHz “Chirped-Pulse Amplification (CPA)” system at the University of Colorado (Murnane and Kapteyn)

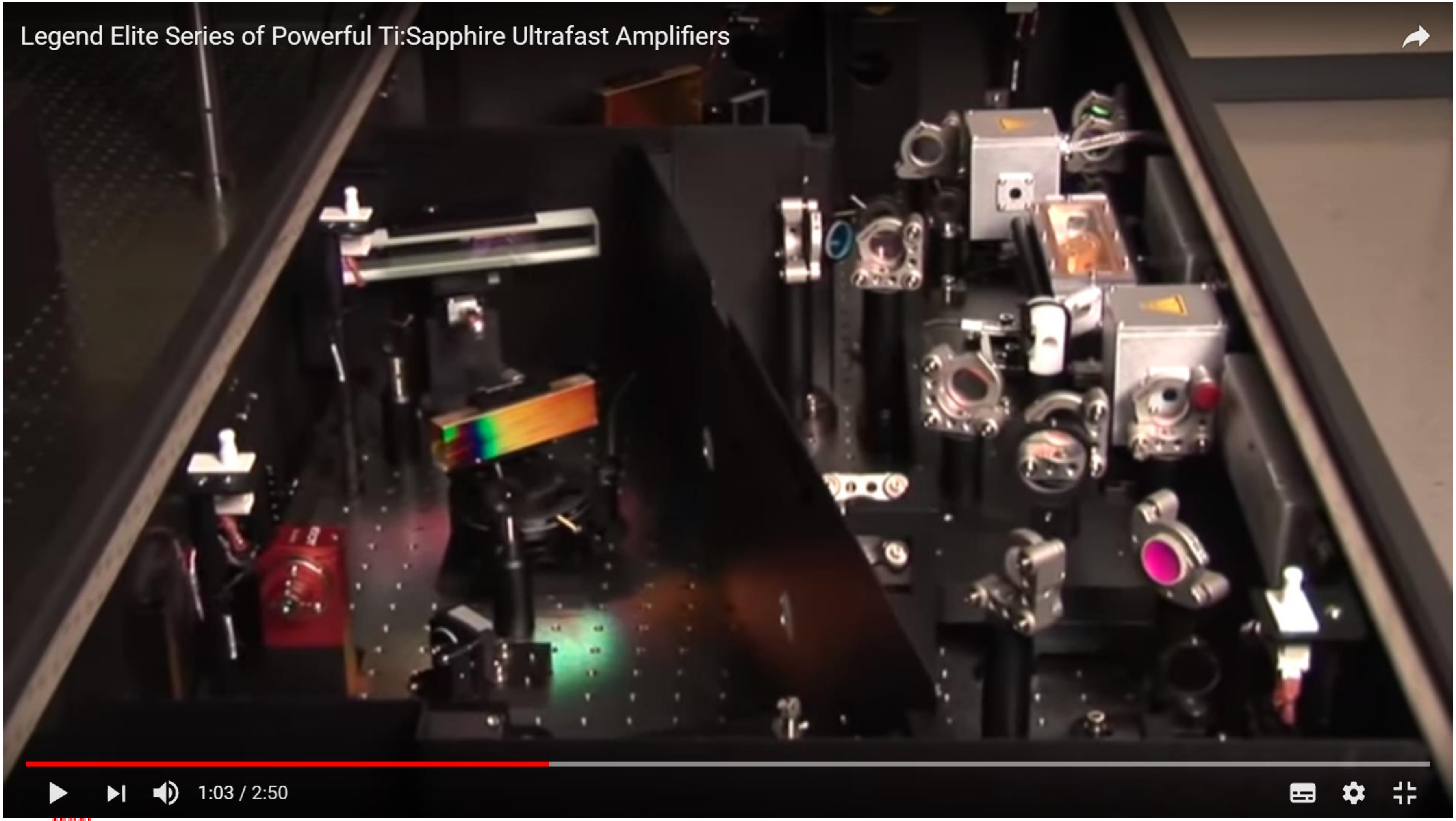
Regenerative amplifier

- https://www.youtube.com/watch?v=zfHwNTaBMGU



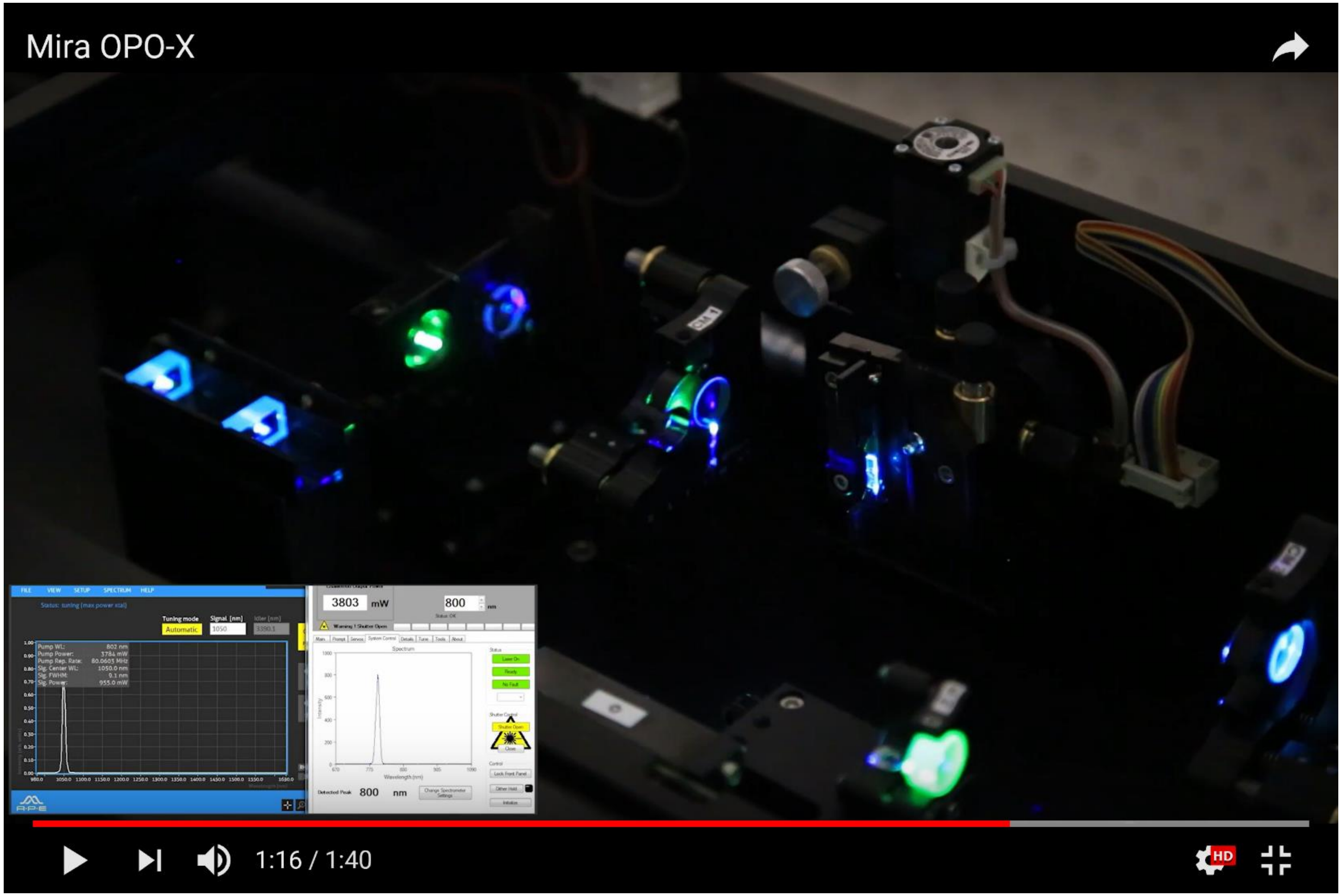
Regenerative amplifier system

- https://www.youtube.com/watch?v=Li2PGff4fVw

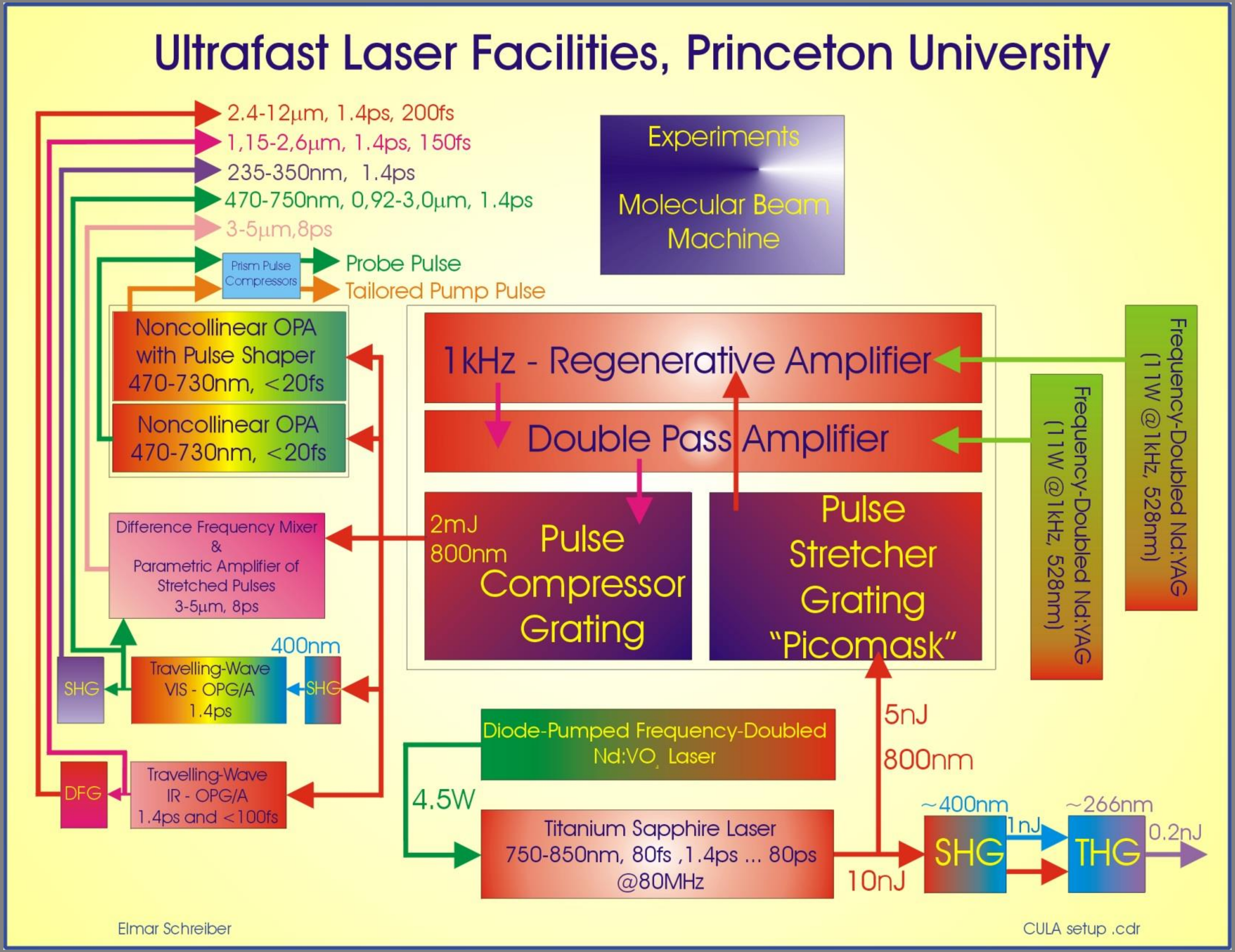


OPO system

- https://www.youtube.com/watch?v=c77xhj7bSl0

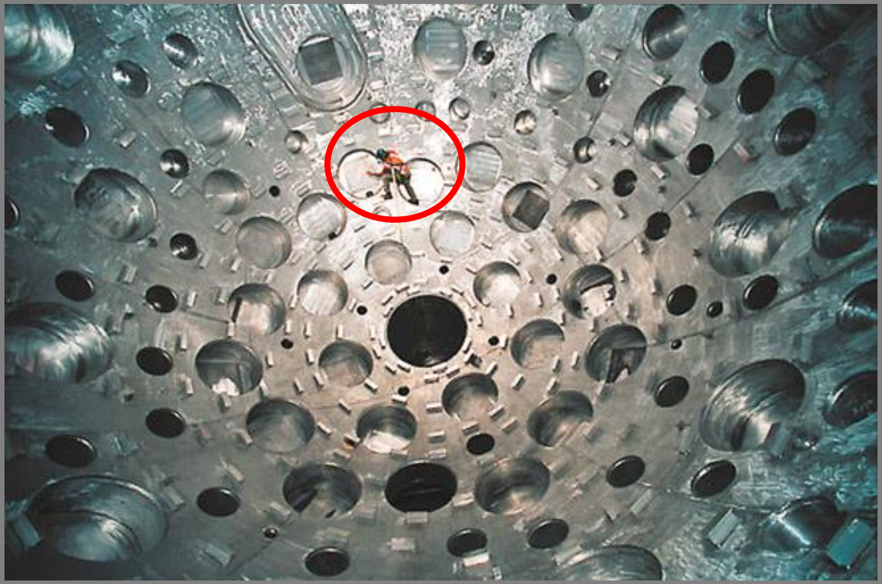


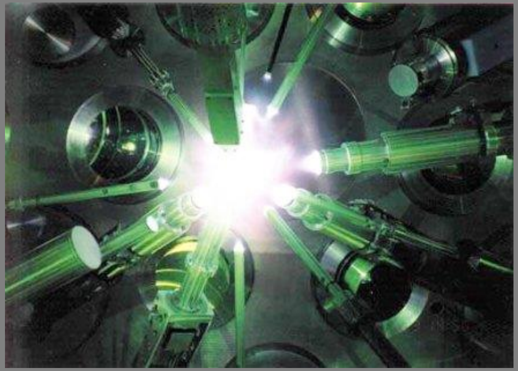
Ultrafast set-ups can be very sophisticated.



國家點火設施（英語：**National Ignition Facility**，縮寫：**NIF**），又稱**國家點燃實驗設施**[1]，是美國的一座雷射型核融合裝置（Inertial confinement fusion, ICF)。

這個設施由勞倫斯利福莫耳國家實驗室建造，位於加州的利佛摩市。NIF意圖使用雷射（Laser）達成極大高溫高壓施加於一小粒氫燃料球上啟動核融反應。NIF也是人類史上最大的ICF設施和世界上 最大的鐳射裝置[2]，而且目標是一但點火後就能自給自足長期形成融合能量輸出。截至2013年10月7日，這個設施是第一個從核融（Nuclear Fusion）產生比從雷射（Laser）吸收的能量更多的輸出能量。[3]

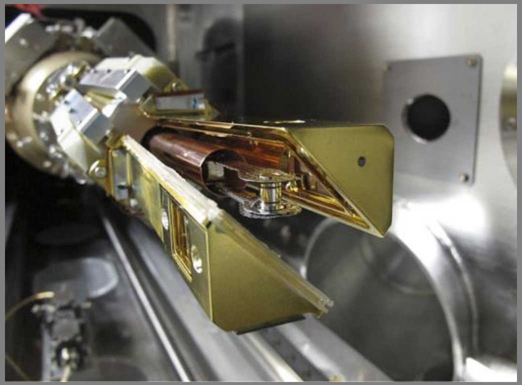


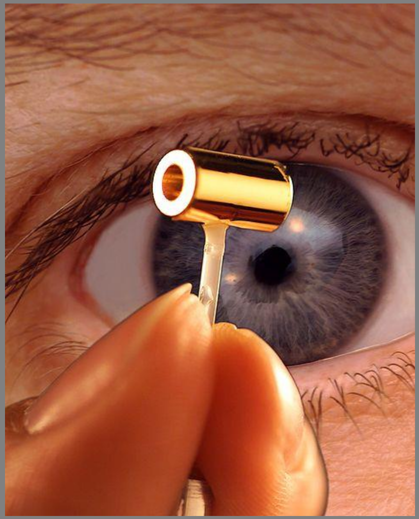


NIF目標是造成500太瓦（TW）能量的雷射在1微微秒的同一瞬間擊中球體。設計中是採用192門總成雷射光束，每四具雷射產生器一組共48組 每組經過16道強化過濾器。

為了保證雷射產生器同步化，所有雷射的最初光源都是來自單一產生器（ILS）再分割強化。因此最初的雷射能量只有一具1053nm的鐿紅外線雷射主控振盪器搭配光纖引導分裂進入48具擴大器 （PAMs）。擴大器會讓光束循環經過四次釹玻璃，每層增強6焦耳能量。原本的設計中這層擴大器會將建築物分割成兩半。改良設計後可以達到更大功率所以也就縮小了體積。

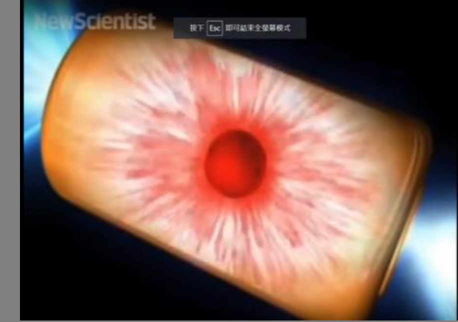
主擴大器原理一樣但是更大且位於雷射末端。發射後第一層擴大器會點燃7,680具高能量氙燈 （每層小擴大器還有自己的氙燈）。所有燈是用大量電容器的能量發出400百萬焦耳（MJ）光能。當光波經過，擴大器會把儲存的能量加入其中，這並非是很有效率的機器，也只有約1/4的能量會成功加入到光束中；所以為了解決這問題光束才要使用光纖導軌進入反射腔重複通過四次。一系列擴大最後會把原本的6焦耳雷射加強到4百萬焦耳。[9]雖然只能維持幾十億分之一秒，但是能量可以達到極高，瞬間超過500TW。





How NIF work

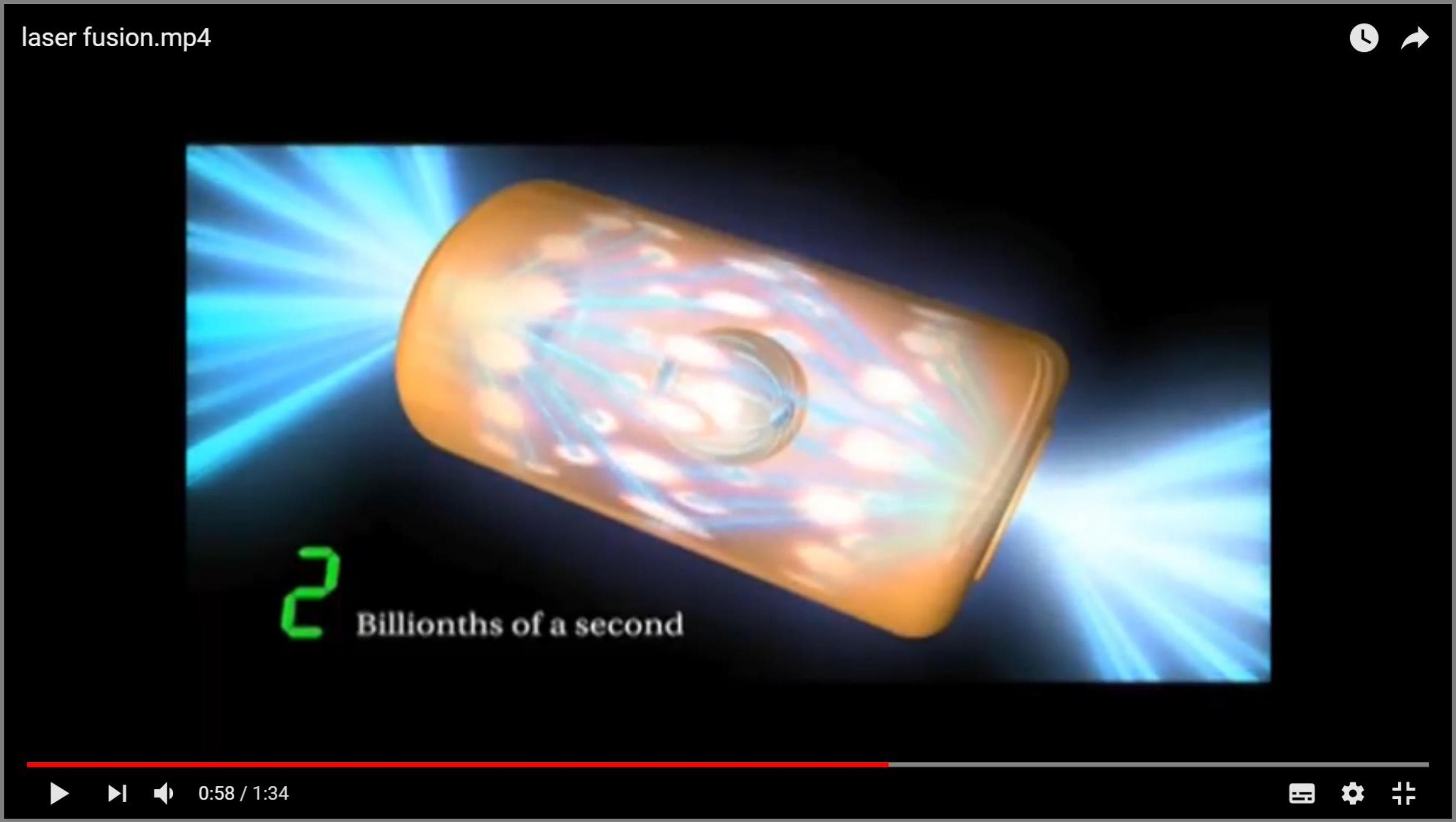
- https://www.youtube.com/watch?v=yixhyPN0r3g

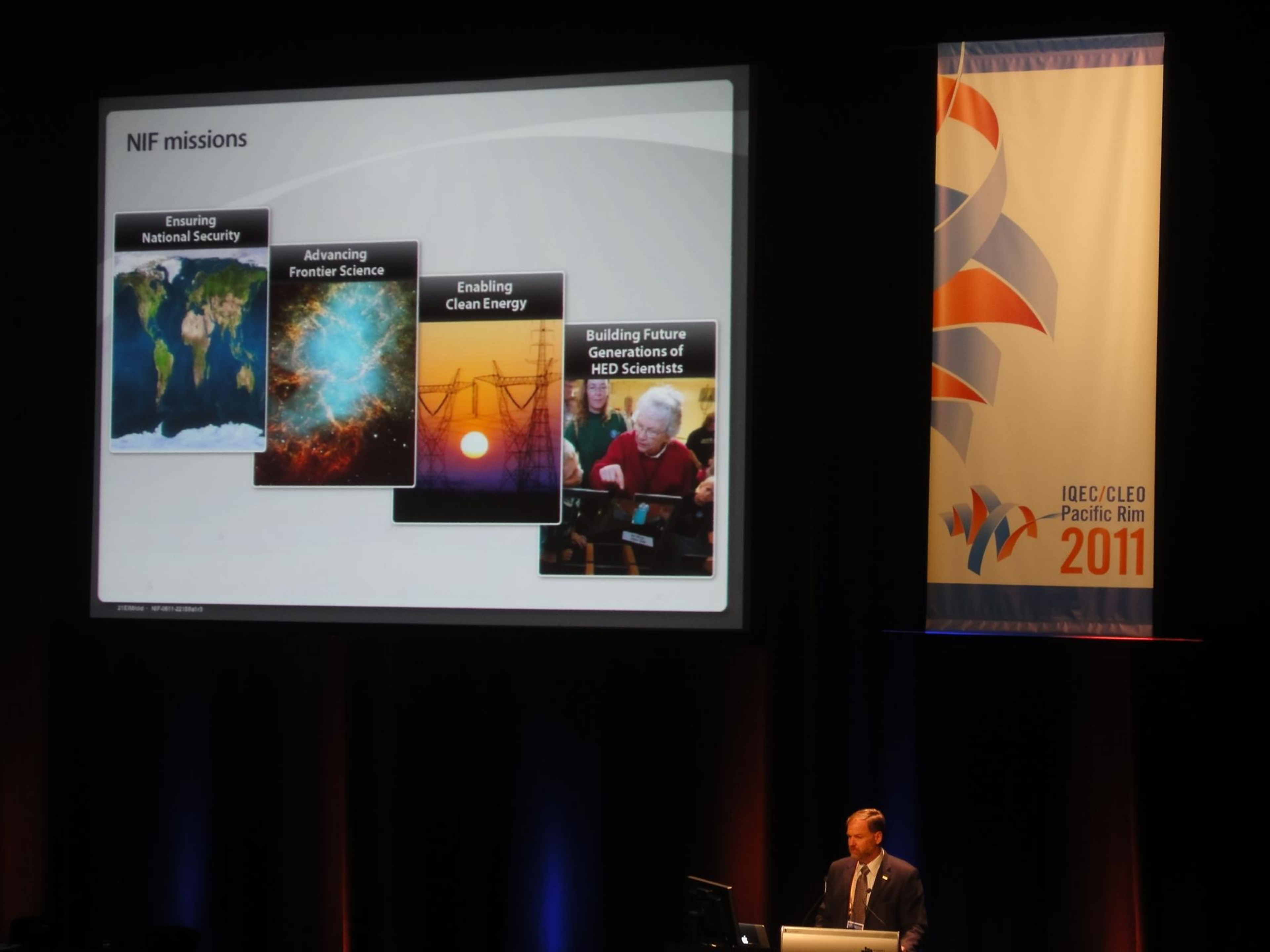


Laser fusion

- https://www.youtube.com/watch?v=Wg8R1lrAiM4

- https://www.youtube.com/watch?v=uIwYQIhMwlw




NIF missions
Ensuring National Security
Advancing Frontier Science
Enabling Clean Energy
Building Future Generations of HED Scientists
IQEC/CLEO
Pacific Rim
2011

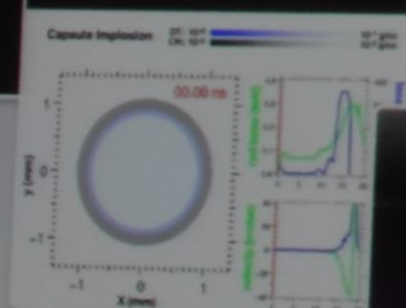
Four steps to ignition

We are taking a systematic approach to learning and improving our engineering design to achieve ignition

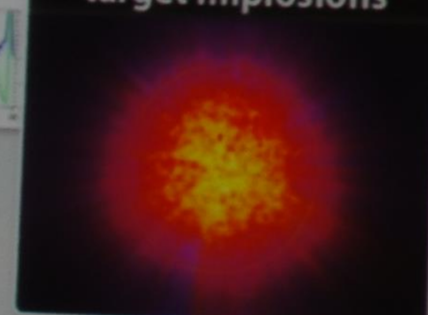
Commission NIF

Commission hohlraum

Commission capsule



Commission layered target implosions



The Dilemma

- In order to measure an event in time, you need a shorter one.
- To study a soap bubble popping, you need a strobe light pulse that's shorter.
- But then, to measure the strobe light pulse, you need a detector whose response time is even shorter.
- And so on…

So, now, how do you measure
the *shortest* event?