中央研究院

Intense laser based on chirped pulse amplification

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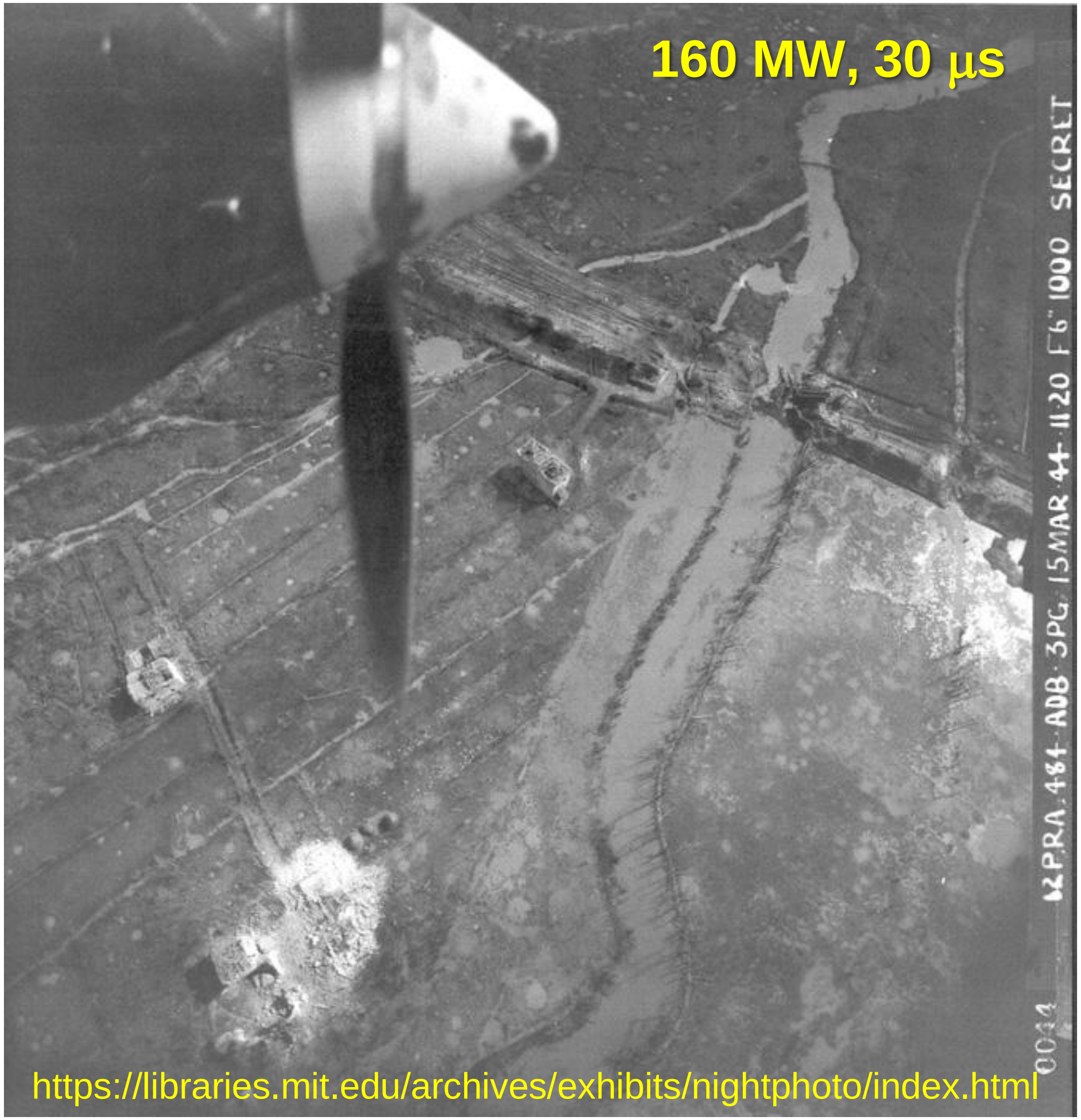
Basic physics of ultra-short pulse lasers

From microsecond to femtosecond by exploiting nonlinear effects

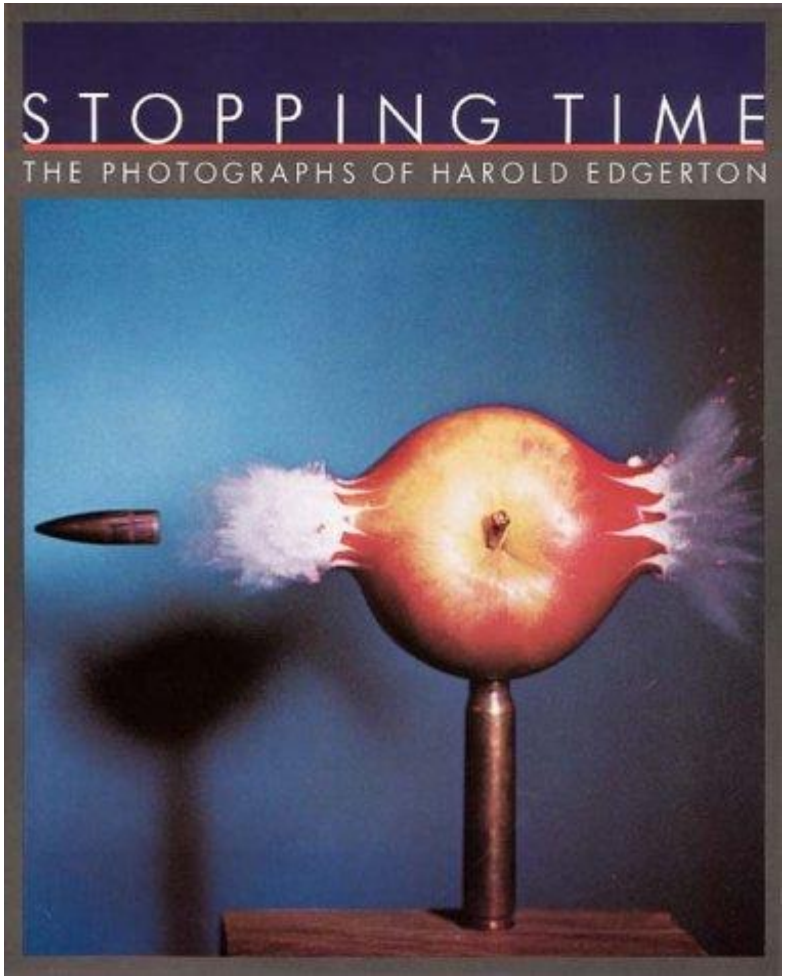
Photography using intense light pulse

World War II Nighttime Aerial Reconnaissance Photograph
March 15, 1944



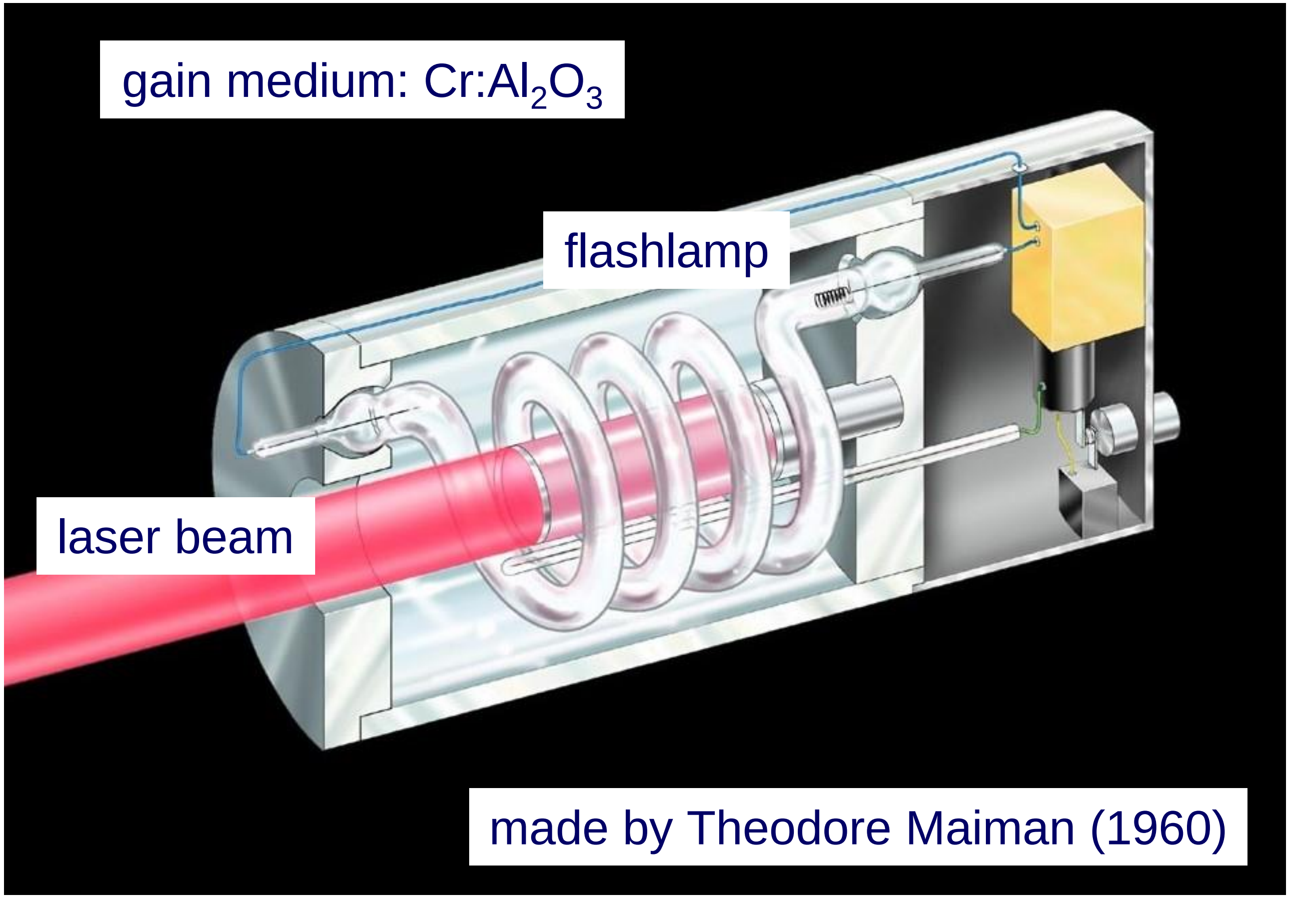
A famous picture taken with 1-μs flash light

The bullet moved less than 1 mm during the flash



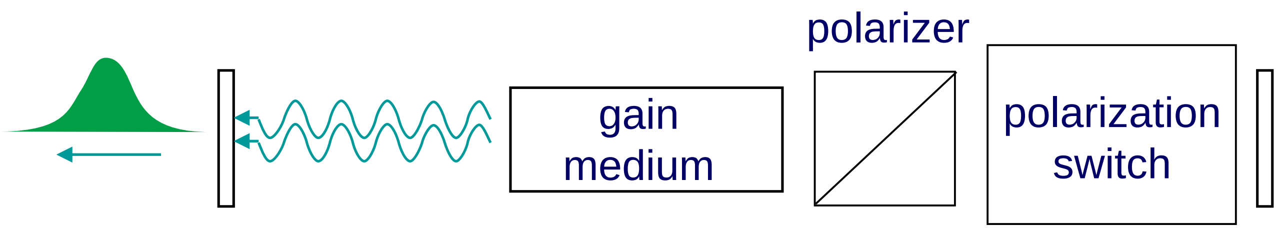
https://www.amazon.com/Stopping-Time-Photographs-Harold-Edgerton/dp/0810927179

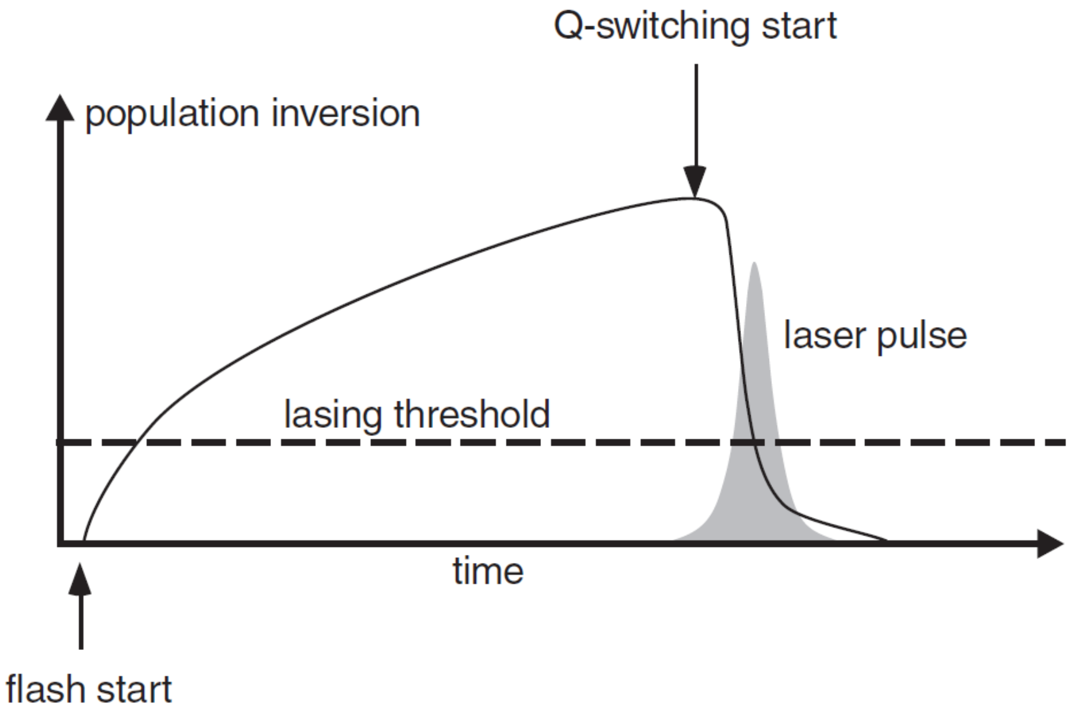
The first laser: ruby laser



Campbell, E.M.. *Laser Programs, the first 25 years, 1972-1997*. United States: N. p., 1998. Web. doi:10.2172/16710.

Producing nanosecond pulse by Q-switching





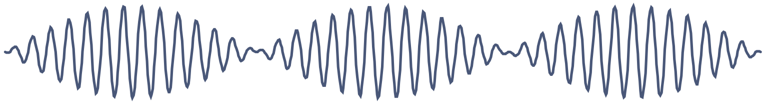
peak power: 100 MW

pulse duration: 10 ns

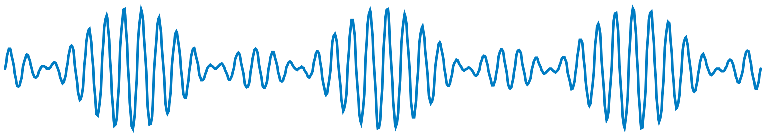
pulse duration limited by roundtrip time

Adding multiple modes to shorten the pulse

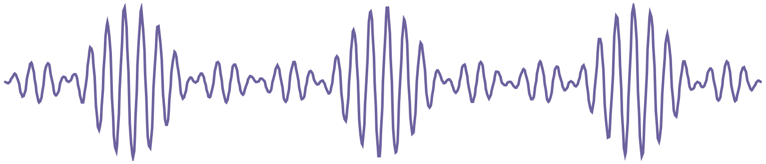
2-mode superposition



3-mode superposition
with phases aligned



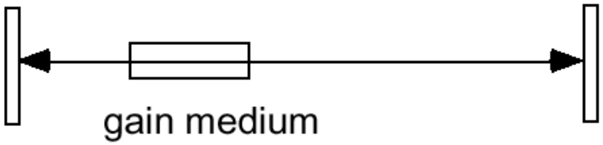
4-mode superposition
with phases aligned



10-mode superposition
with phases aligned

10-mode superposition
with random phases

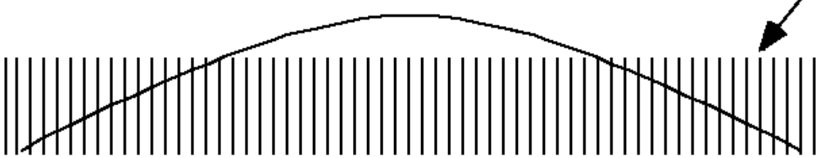
Broadband mode-locking



resonance condition: $\dfrac{n\lambda}{2} = L$

gain bandwidth $= 10^{12} - 10^{14}$ Hz

cavity mode spacing $= \dfrac{\omega_c}{2\pi} \approx 10^8$ Hz



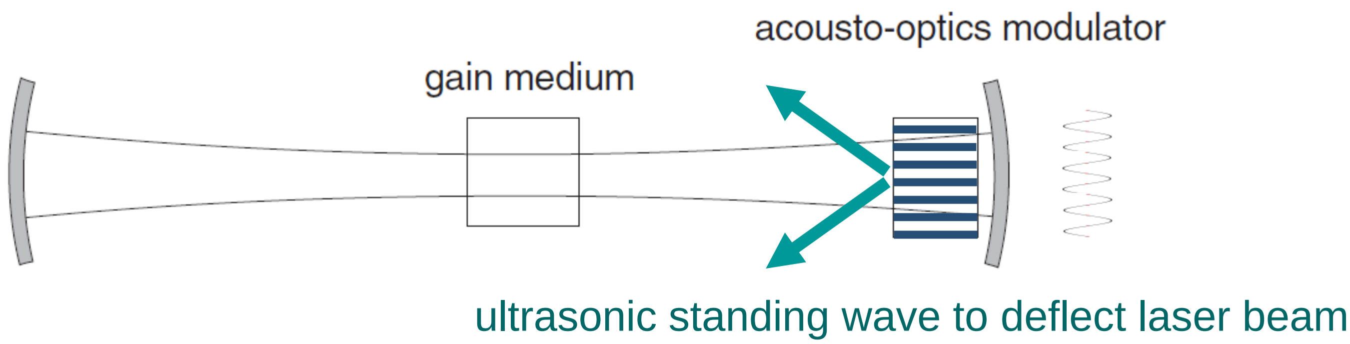
phase alignment ⟶ pulses much shorter than the (nanosecond) round-trip time

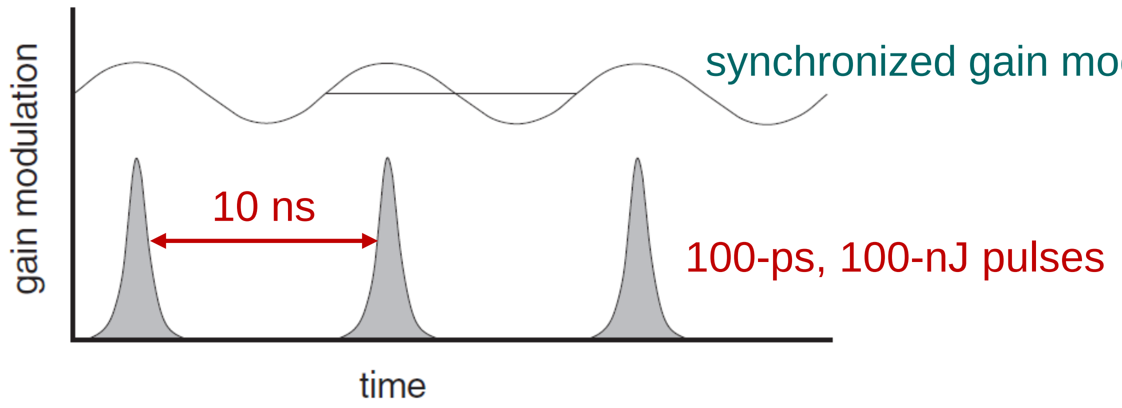
$$\left| \sum_{m=-n/2}^{n/2} e^{i(\omega_0 + m\omega_c)t} \right| = 1 + 2 \sum_{m=1}^{n/2} \cos(m\omega_c t) = \frac{\sin\left[\frac{(n+1)\omega_c t}{2}\right]}{\sin\frac{\omega_c t}{2}}$$

height $\propto n$

width $\propto n^{-1}$

Active mode-locking

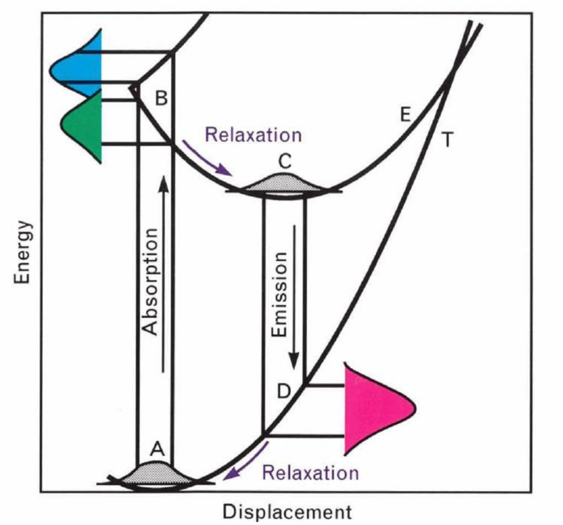




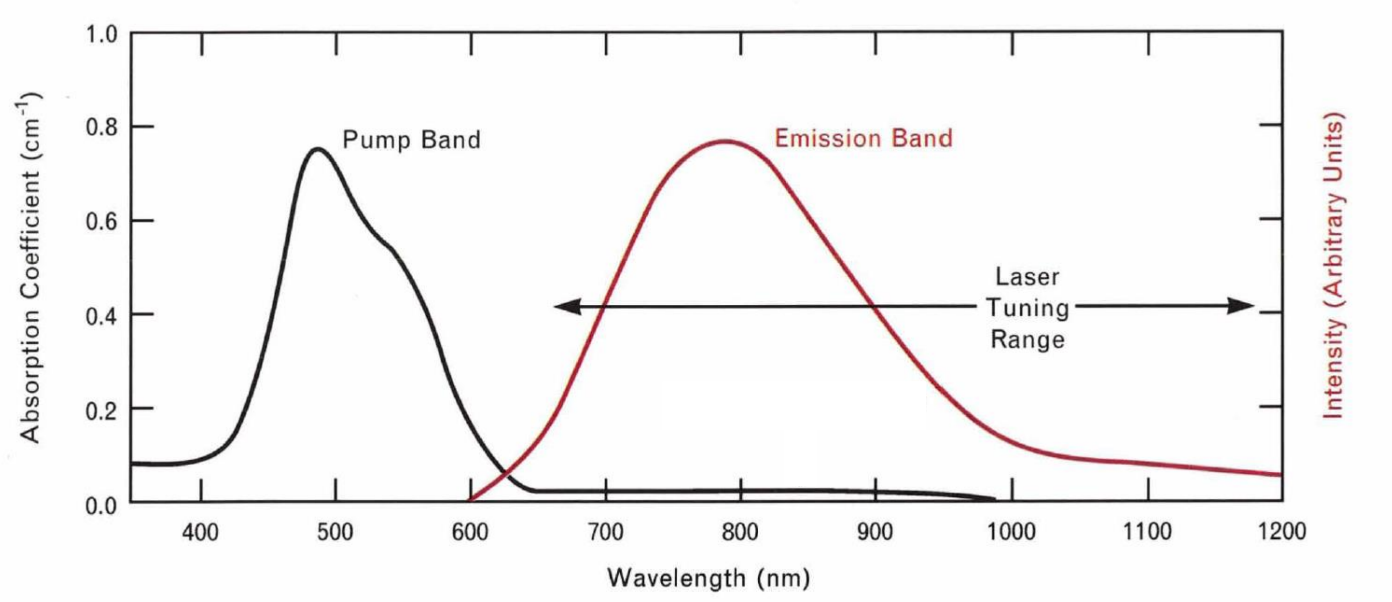
Limitation:

- Pulse shortening effect weakens as the pulse shortens.
- Small gain bandwidth narrows the pulse spectrum, thus broadens the pulse.

Ti:sapphire laser



- Bandwidth: 700-1000 nm
- Saturation fluence: 0.9 J/cm^2
- Heat conductivity: 0.42 W/cm$^{\circ}$K
- Damage threshold: 23 GW/cm^2 at 200 ps

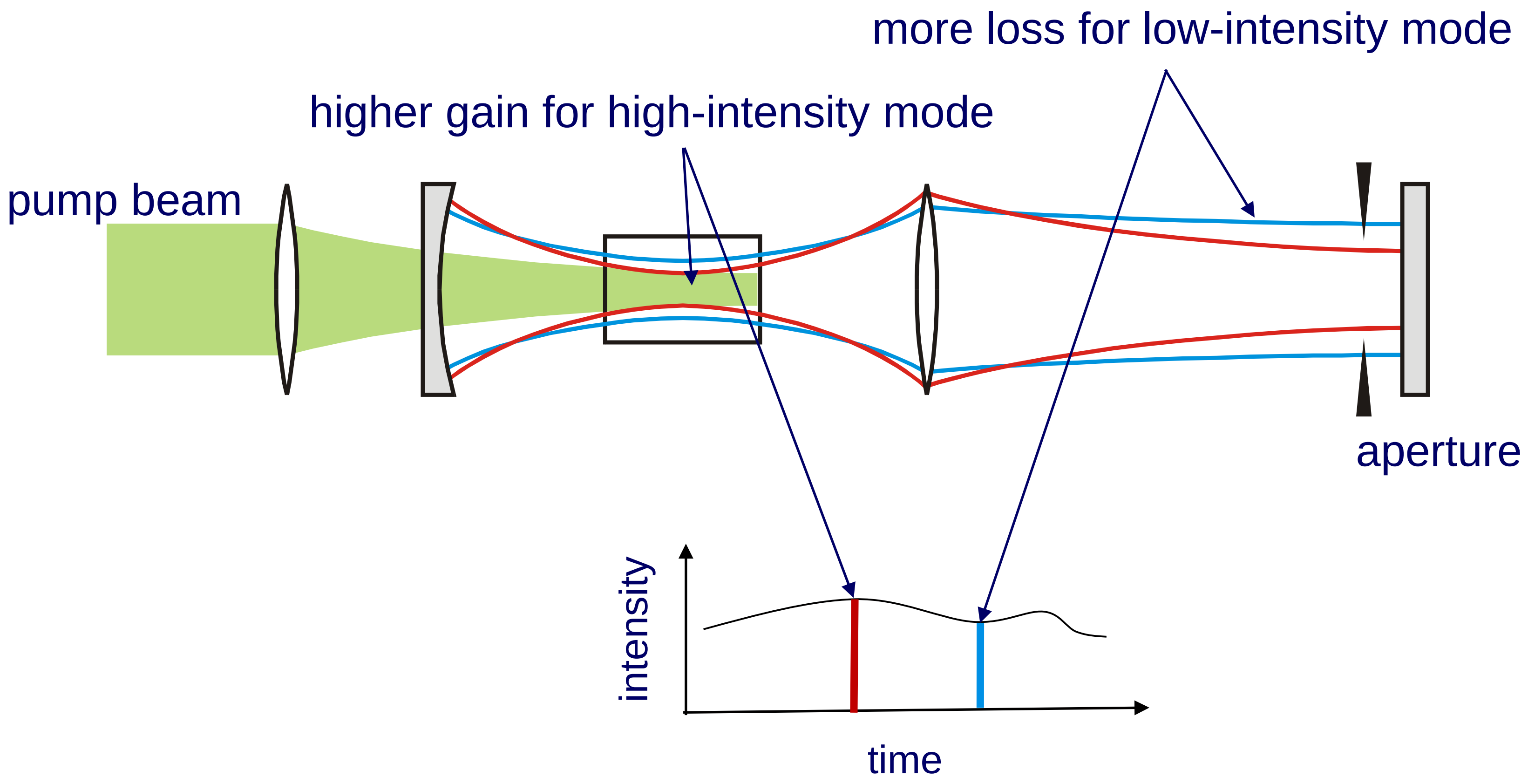


Lincoln Laboratory Journal **3**, 447 (1990)

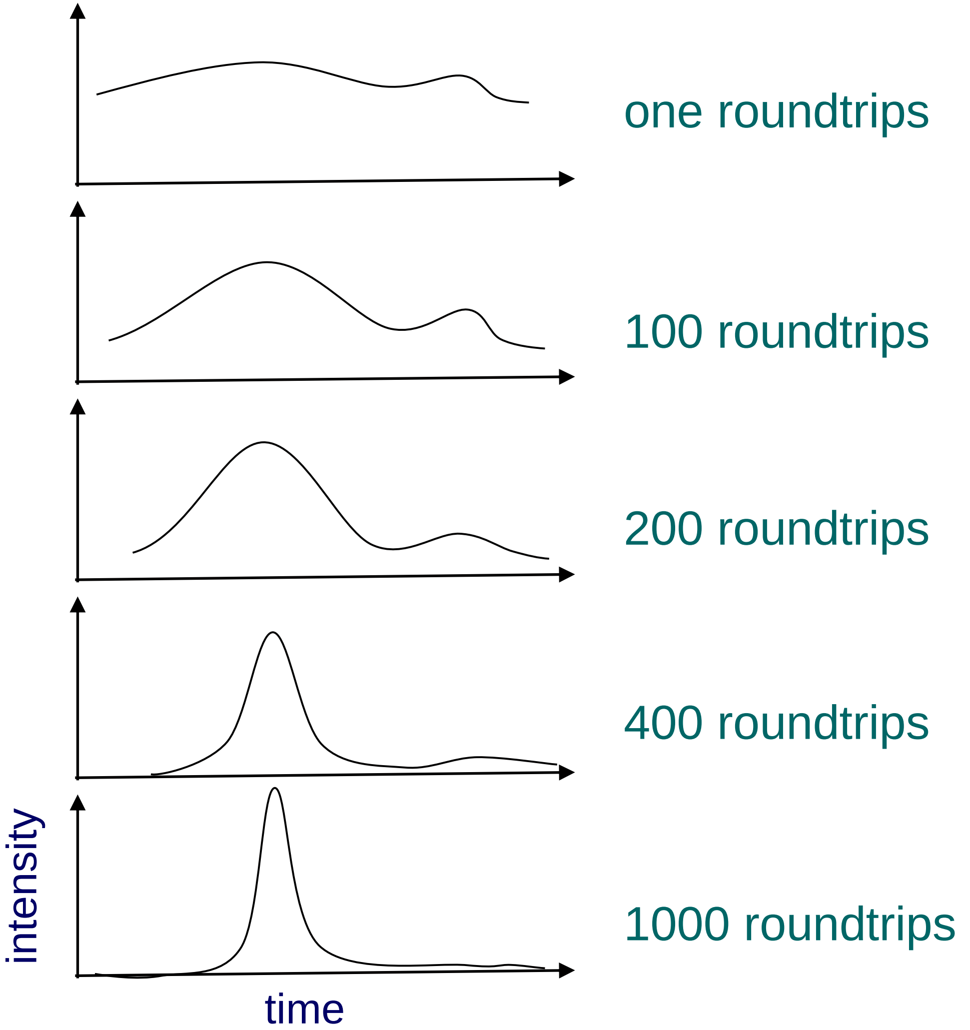
Intracavity pulse compression by self-focusing

optical Kerr effect: a small dependence of refractive index on intensity

$$n = n_0 + n_2 I \longrightarrow \text{intracavity self-focusing}$$

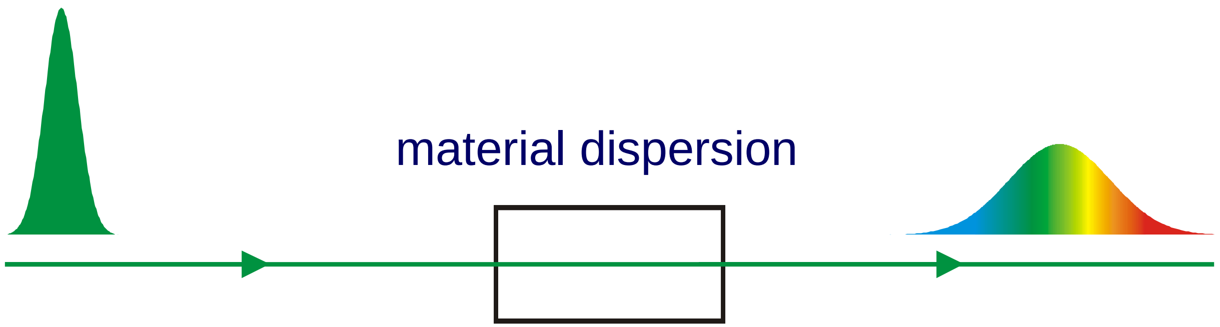


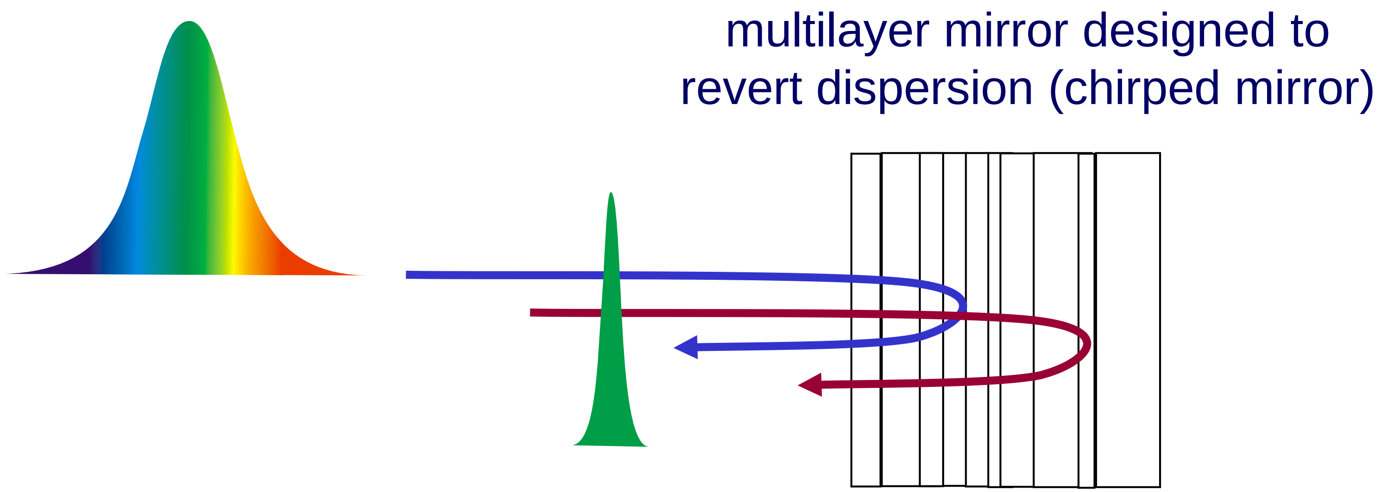
Capitalism in a laser cavity



Pulse duration is eventually limited by gain bandwidth and dispersion.

Compensation for intracavity dispersion



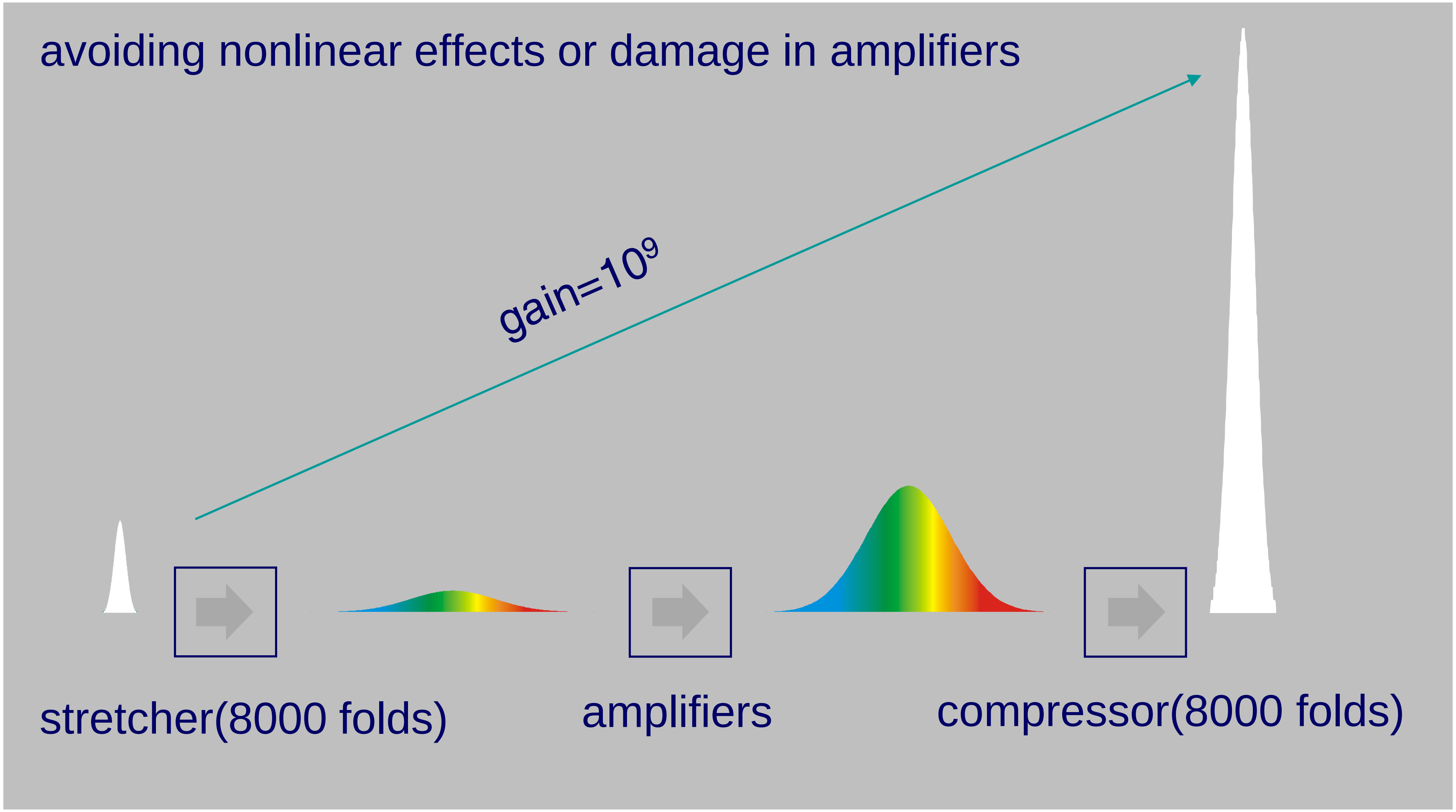


Amplifying femtosecond pulses

Avoiding nonlinear effects by first stretching and then compressing

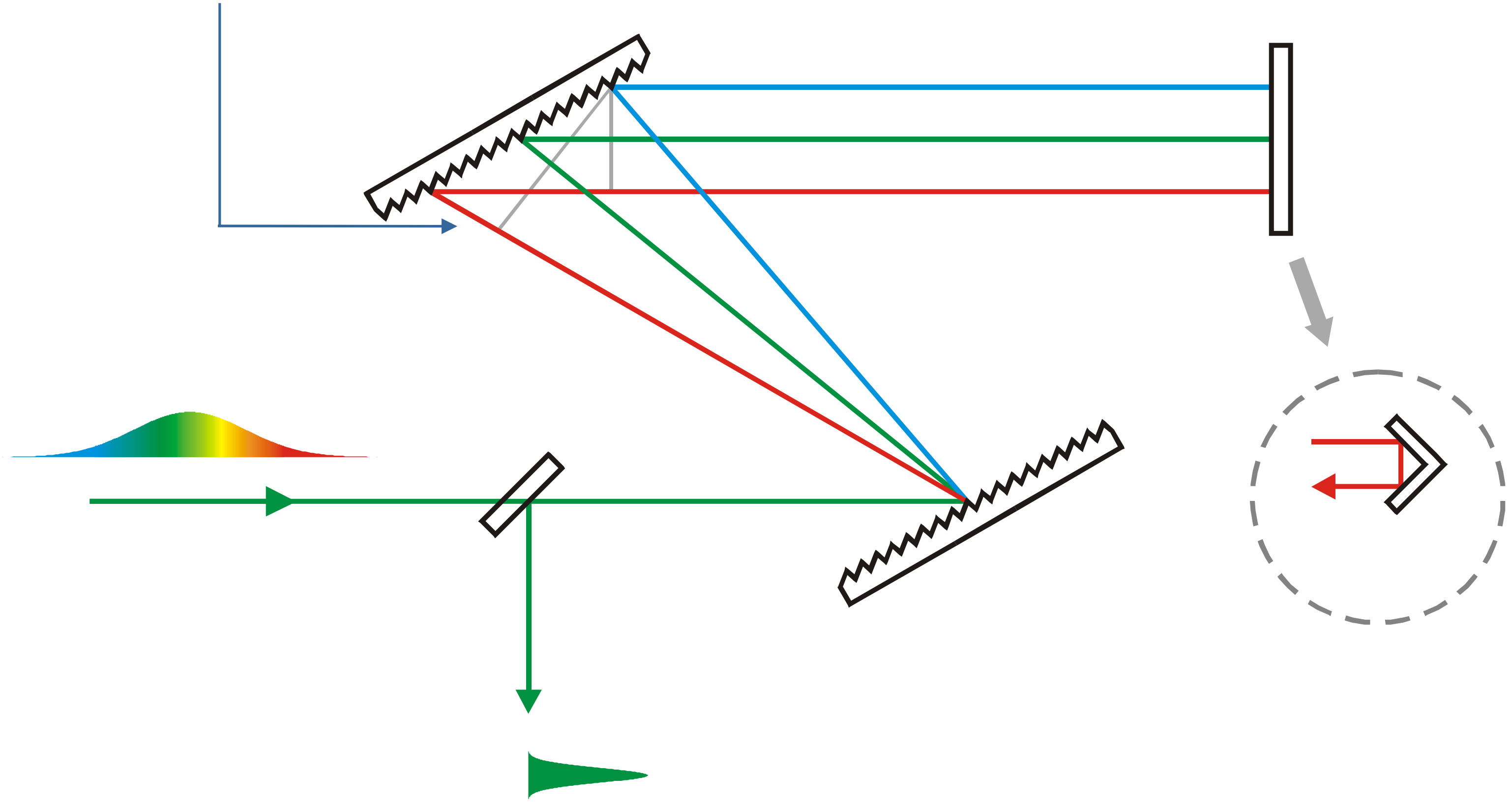
Chirped pulse amplification

Invented by D. Strickland and G. Mourou, Nobel Prize in Physics 2018



Principle of pulse compressor

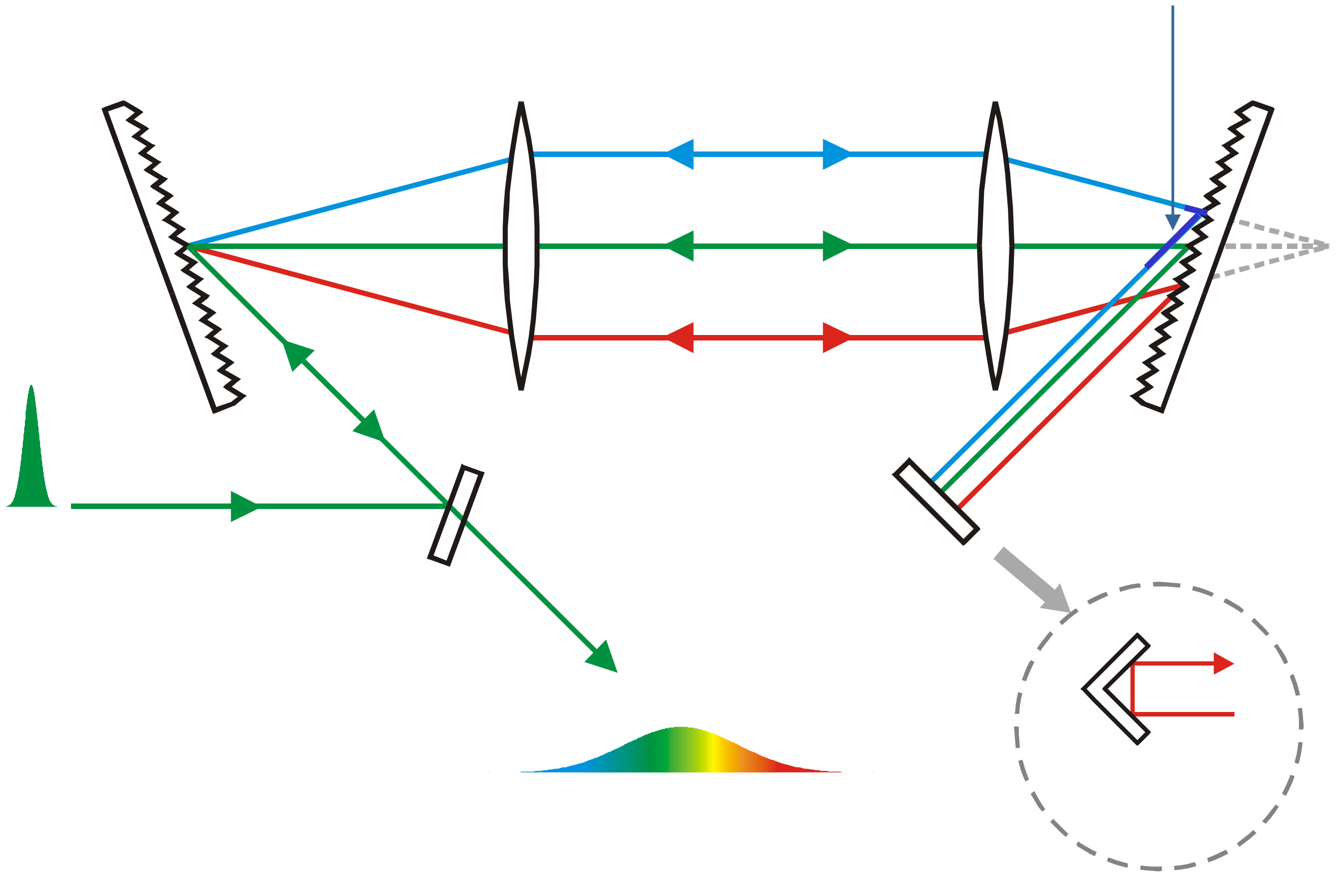
Longer wavelength has longer optical path, the difference is comparable to grating size.



E. B. Treacy, Optical pulse compression with diffraction gratings, IEEE J. Quant. Electron QE-5, 454 (1969).

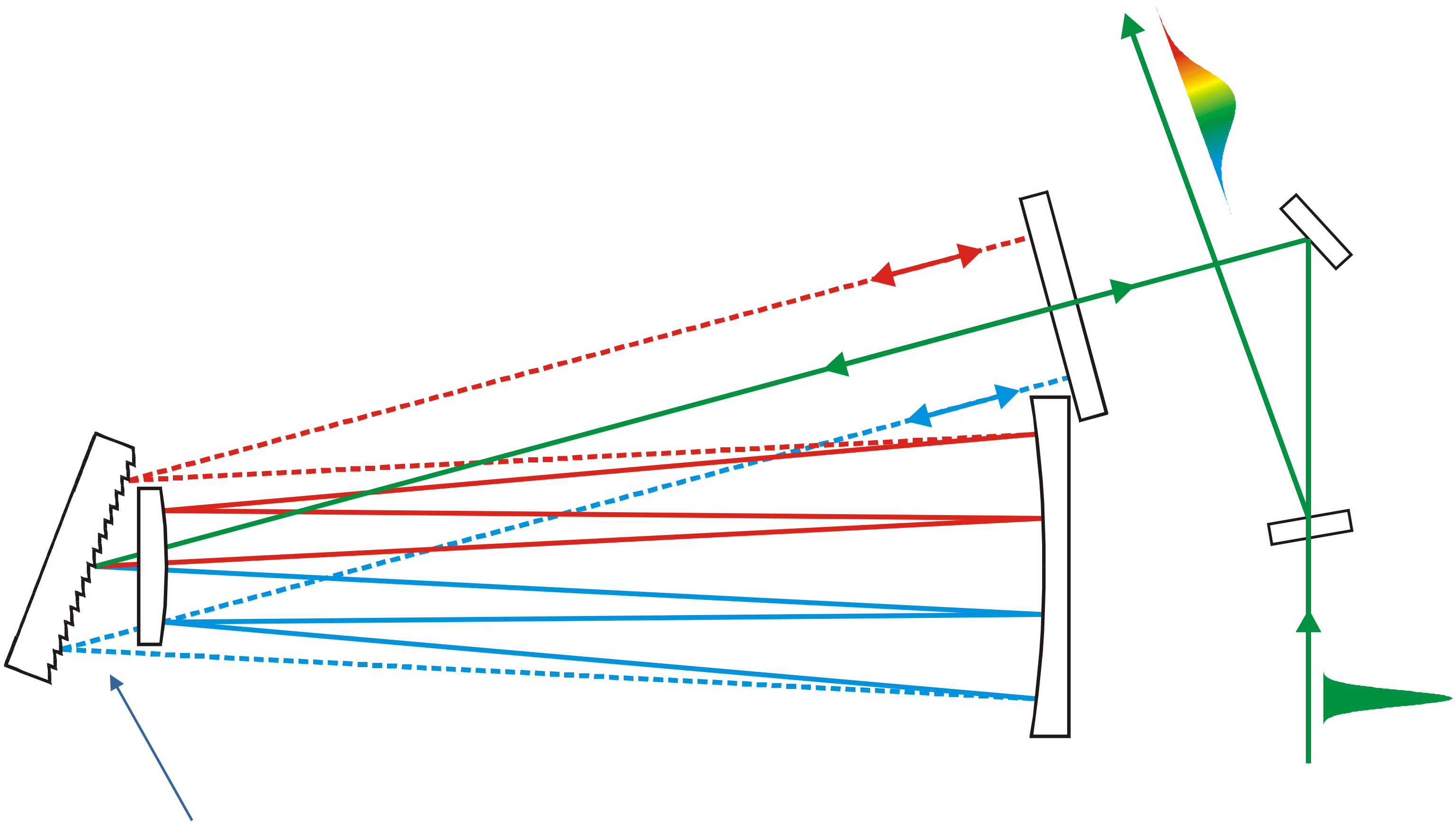
Principle of pulse stretcher

Shorter wavelength has longer optical path, the difference is comparable to grating size.



O. E. Martinez, J. P. Gordon, and R. L. Fork, Negative group-velocity dispersion using refraction, J. Opt. Soc. Am. A **1**, 1003 (1984).

Reflective pulse stretcher

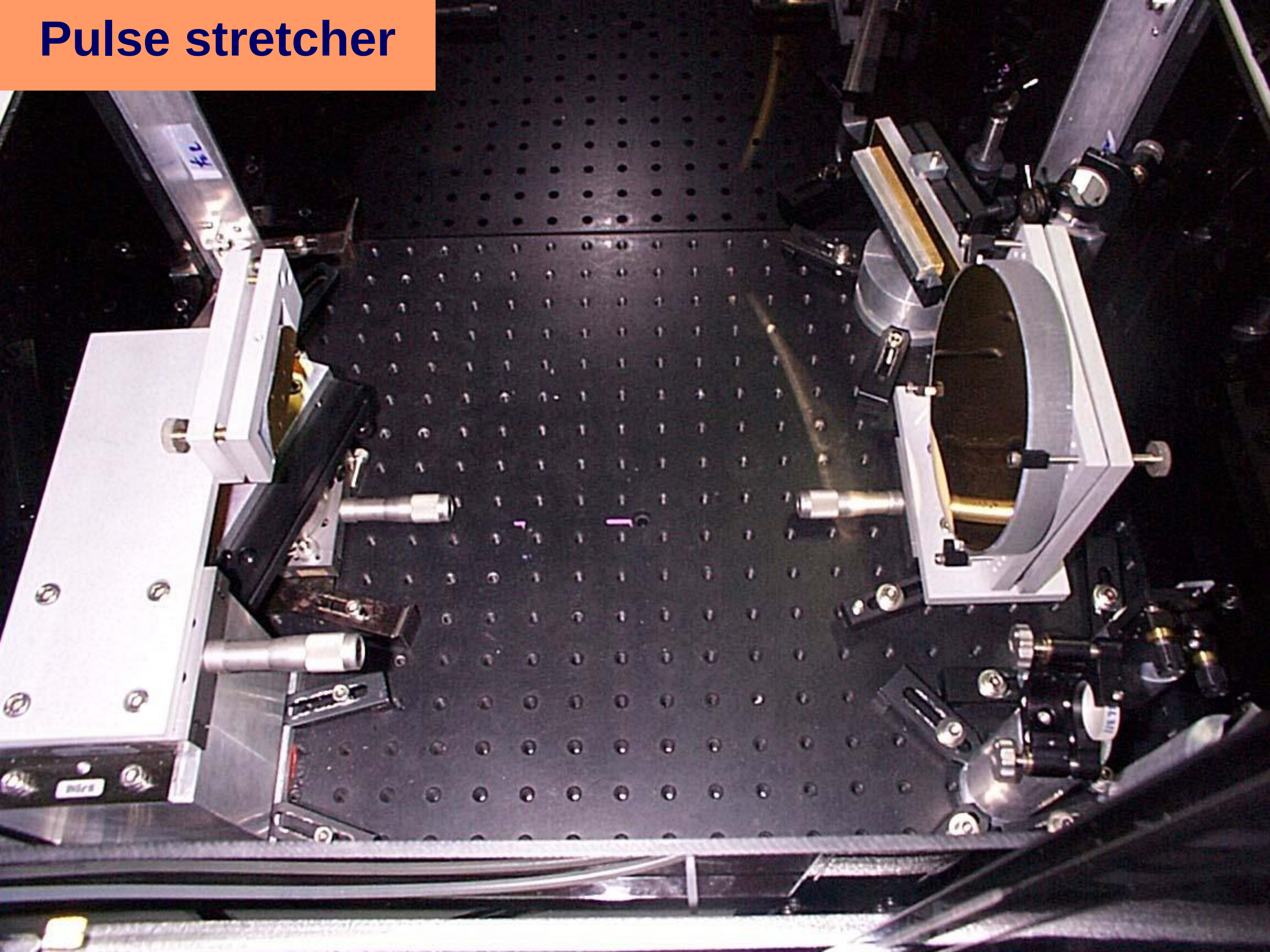


longer optical path for shorter wavelength

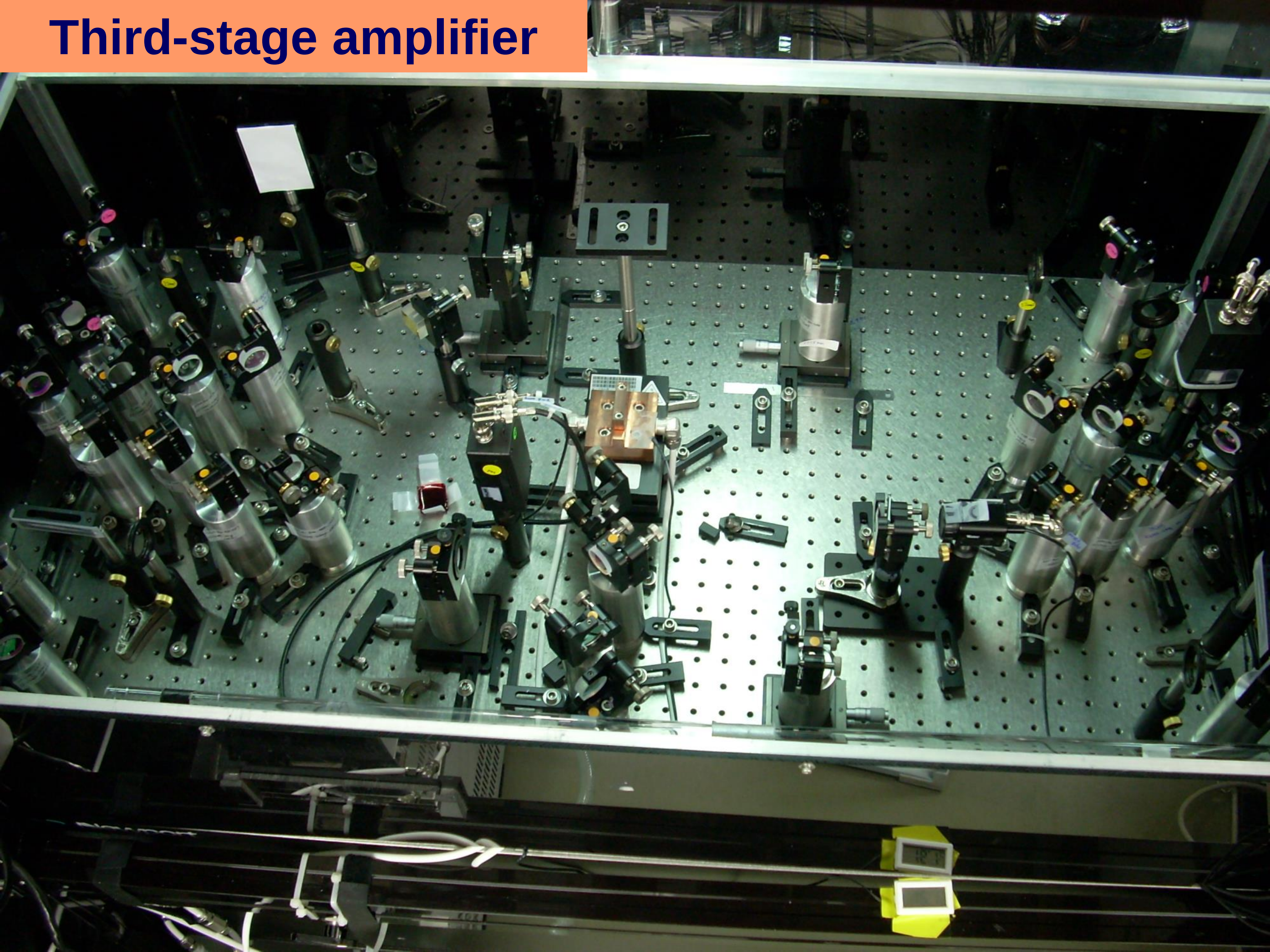
The 100-TW laser at Nat'l Central Univ.

A home-grown example of chirped pulse amplification

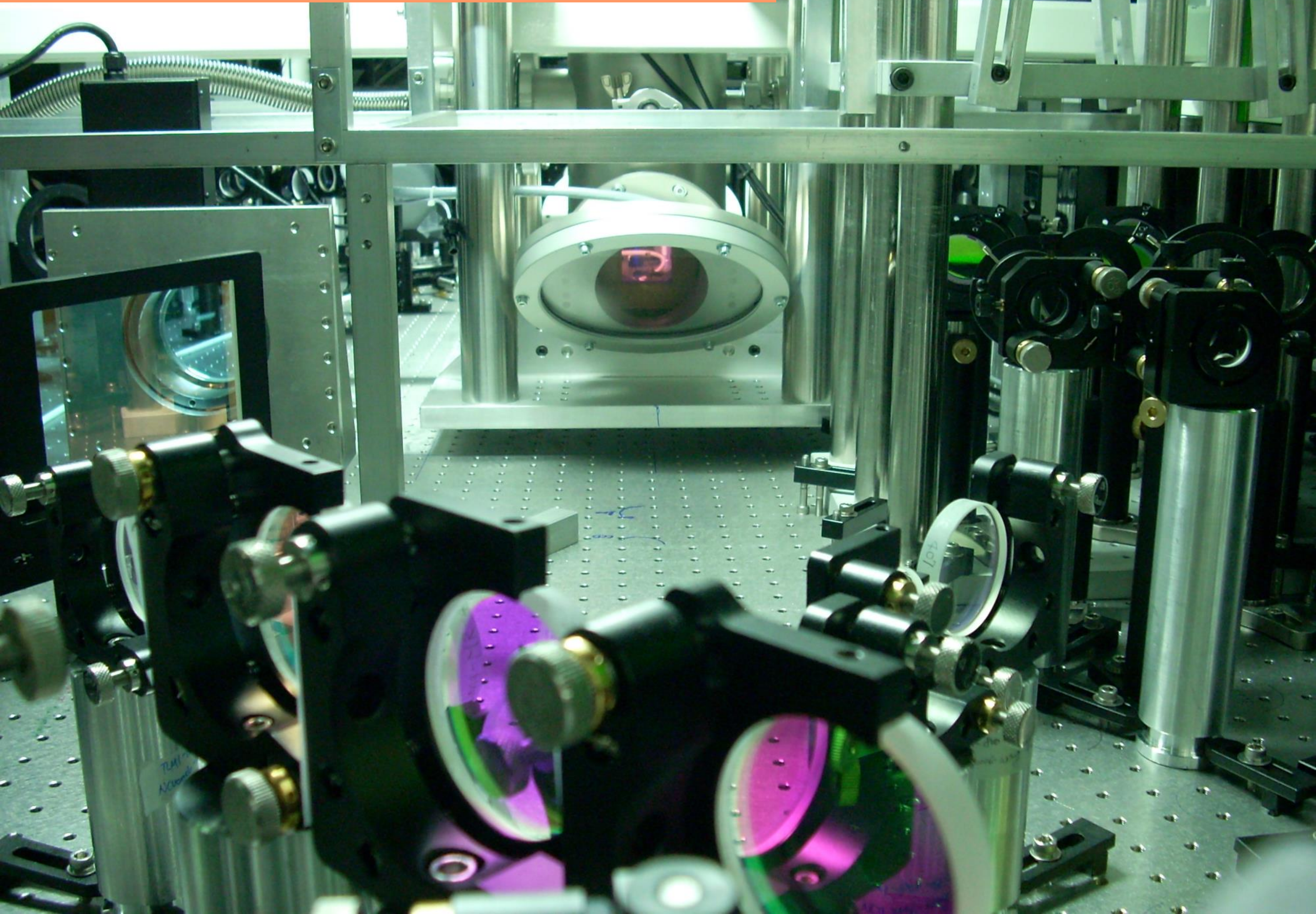
Pulse stretcher



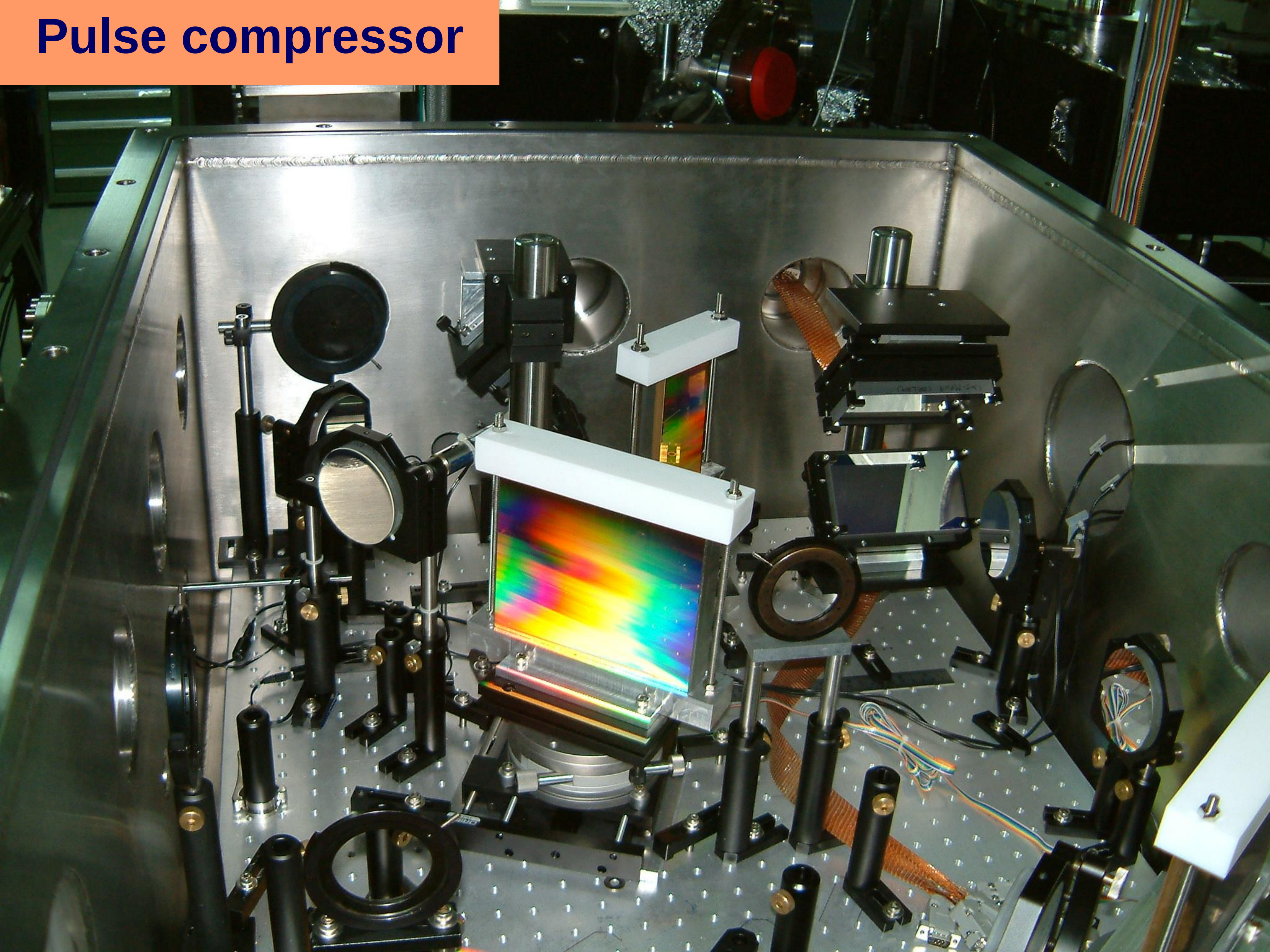
Third-stage amplifier



100-TW final stage amplifier



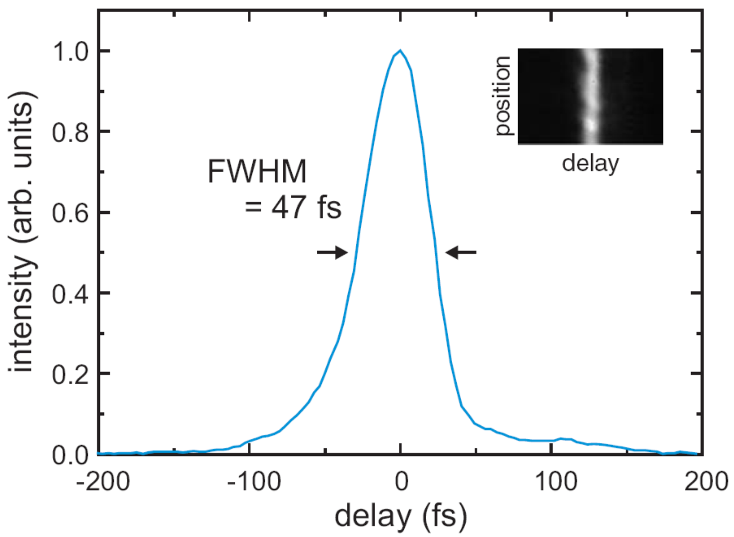
Pulse compressor

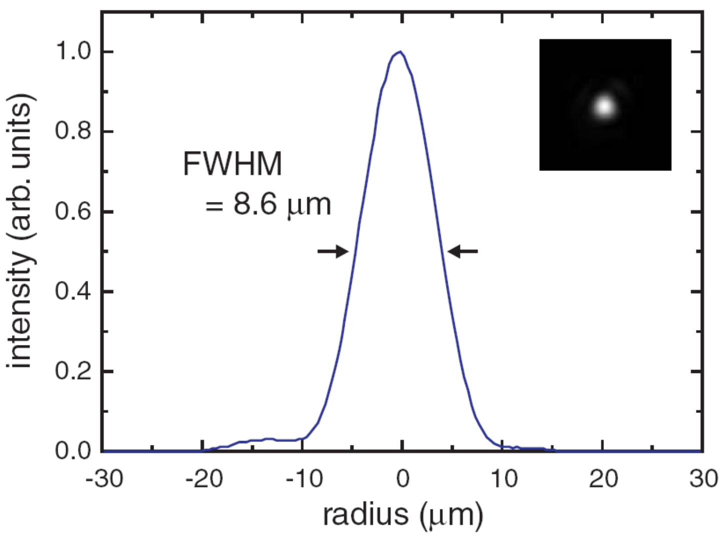


Compressor array

16 Nd:YAG pump lasers

Compressed and focused pulse at Nat'l Central Univ.





corresponding to a pulse duration of 33 fs

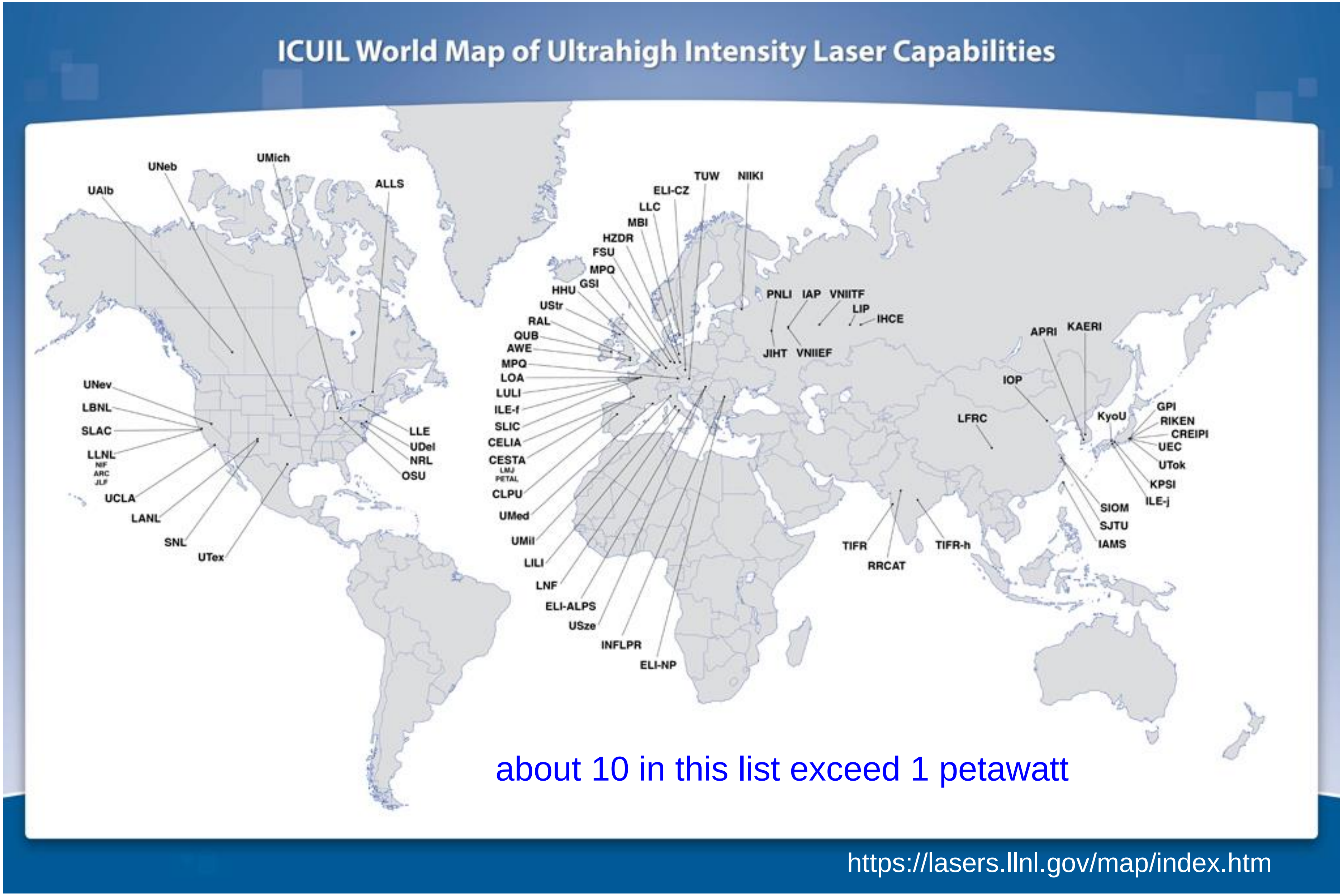
If adaptive mirrors are used, it is possible to focus down to 1-μm diameter.

Appl. Phys. B **117**, 1189 (2014)

100-TW laser focused to 10-μm diameter

- peak power: 3J/30 fs =10^{14} W (10,000 nuclear power plants)
- peak intensity: 10^{20} W/cm^2 (sunshine at noon = 0.1 W/cm^2)
- electric field: 3.2×10^{13} V/m (50× Coulomb field in hydrogen)
- optical pressure: 6.7×10^{10} atm (1/4× center of the Sun)
- plasma temperature: 10^7 K (center of the Sun)
- acceleration on electron: 5×10^{23} g (near a black hole)
- energy density: 10^9 J/cm^3 (B83 H-bomb, 1.2 MT of TNT)

World map of ultrahigh intensity lasers

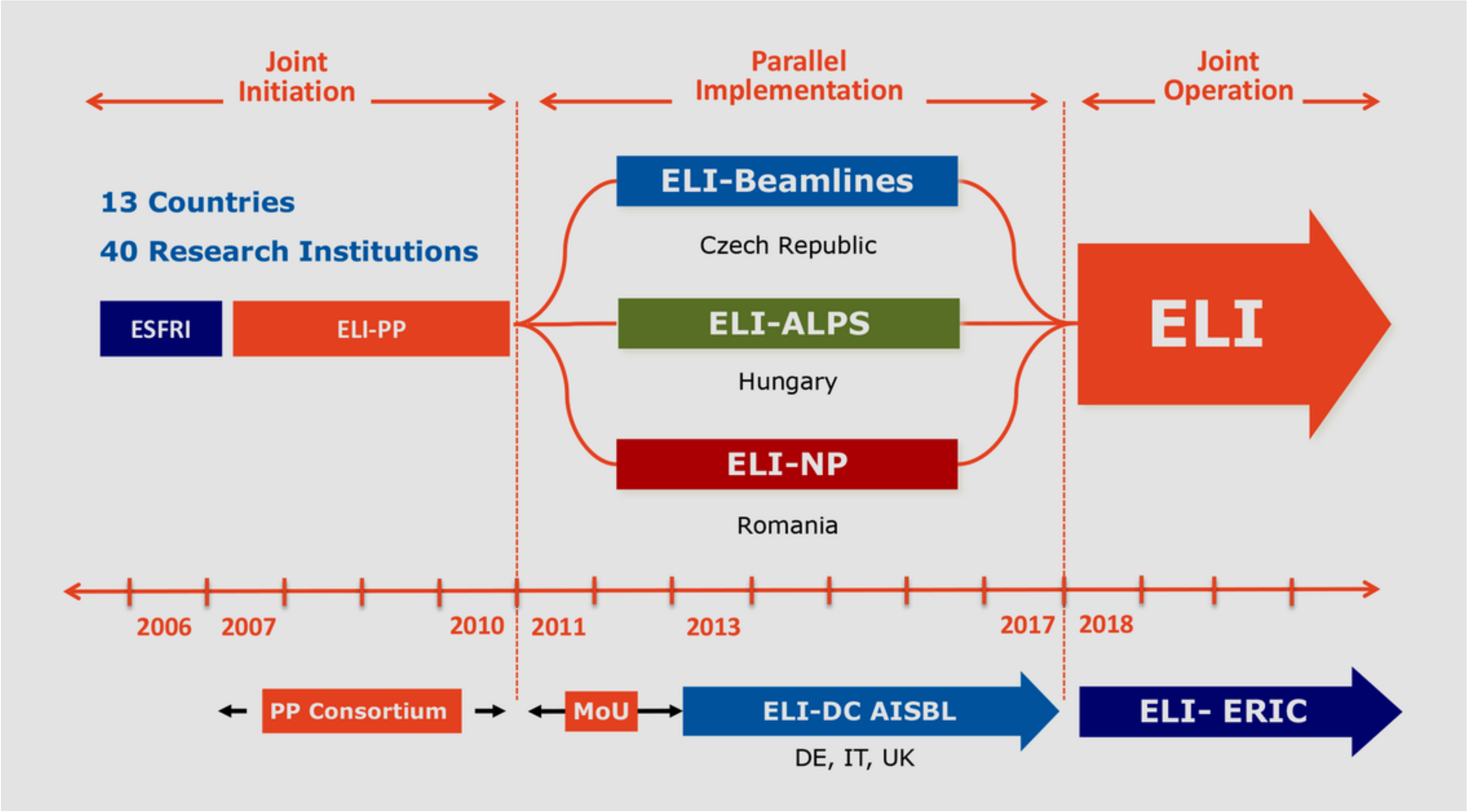


about 10 in this list exceed 1 petawatt

https://lasers.llnl.gov/map/index.htm

Extreme light infrastructure in EU

Initiated by Gerard Mourou



ELI will be a multi-sited Research Infrastructure for the investigation and applications of laser matter interaction at more than 6 orders of magnitude higher intensities than today's state of the art.

https://www.eli-beams.eu/en/about/eli-infrastructure/

Extreme light infrastructure in EU

Initiated by Gerard Mourou

ELI will comprise several different branches:

- Attosecond Light Pulse Source (ELI-ALPS, Szeged, HU): Attosecond facility providing light between THz and X-ray frequency range for developers and users in the form of ultrashort pulses with high repetition rate.
- ELI-Beamlines (ELI BL, Dolní Břežany, CZ): High-energy beam facility, responsible for development and use of ultra-short pulses of high-energy particles and radiation stemming from the ultra-relativistic interaction.
- Nuclear Physics Facility (ELI-NP, Magurele, RO) User facility with ultra-intense 10 PW laser beam and a brilliant gamma source (up to 19 MeV), enabling also brilliant neutron beam generation with a largely controlled variety of energies.

A fourth site for Ultra-High-Field Science centered on direct physics of the unprecedented laser field strength is yet to be decided.

https://www.eli-beams.eu/en/about/eli-infrastructure/

Where did this Nobel-Prize idea come from?

Strickland worried that the experiment was too simple for a Ph.D. thesis.

First few lines of the CPA paper

D. Strickland and G. Mourou, Compression of amplified chirped optical pulses, Optics Communication **56**, 219 (1985).

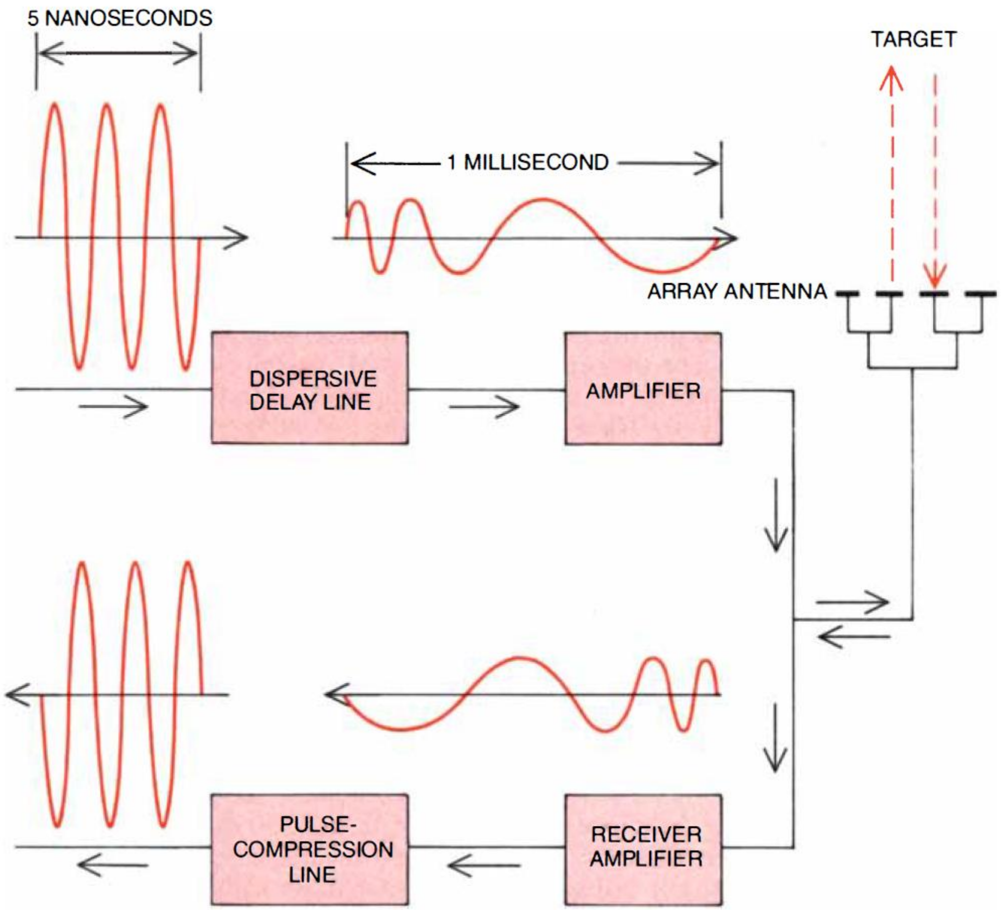
The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The echo is compressed to its original pulse shape by a negatively dispersive delay line [1].

.

We wish to report here a system which transposes the technique employed in radar to the optical regime, and that in principle should be capable of producing short (≈l ps) pulses with energies at the Joule level.

Chirped pulse amplification in radar

Phase array radars, E. Brookner, Scientific American **252**, 94 (Feb.1985).



Strickland and Mourou's paper was submitted at July 1985.

What are chirped pulses in daily life?

汪	high tone	1000 Hz sine wave
王	chirped up	250 → 1000 Hz sine wave
往	low tone	250 Hz sine wave
望	chirped down	1000 → 250 Hz sine wave

歪果仁逼角不灰使傭 chirped pulse

Where did the large bandwidth come from?

Large bandwidth is required for the stretcher
and the compressor.

The first passively mode-locked Ti:sapphire laser

October 15, 1989 / Vol. 14, No. 20 / OPTICS LETTERS 1125

Femtosecond passively mode-locked Ti:Al_2O_3 laser with a nonlinear external cavity

J. Goodberlet, J. Wang, and J. G. Fujimoto

Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

P. A. Schulz

Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02173

Received June 2, 1989; accepted August 2, 1989

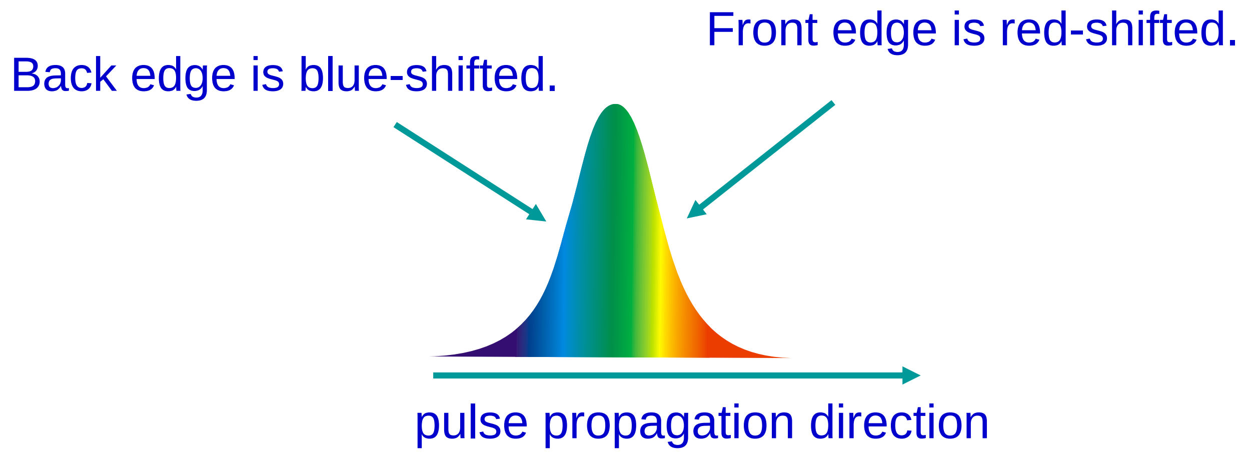
Ultrashort pulses are generated in a Ti:Al_2O_3 laser by using a coupled nonlinear external cavity. The external cavity uses self-phase modulation in an optical fiber to achieve passive mode locking without the need for synchronous pumping or acousto-optic modulation. A stable train of chirped 1.4-psec pulses is generated. After dispersive compensation, pulses as short as 200 fsec are obtained.

Kerr-effect produces up-chirped pulses, ready for compression

optical Kerr effect: $n = n_0 + n_2 I$

$$\phi(x,t) = knx - \omega t = k[n_0 + n_2 I(t)]x - \omega t$$

$$\omega' = -\frac{\partial \phi}{\partial t} = \omega - kn_0 \frac{\partial I(t)}{\partial t}$$



12X pulse compression by self-phase modulation

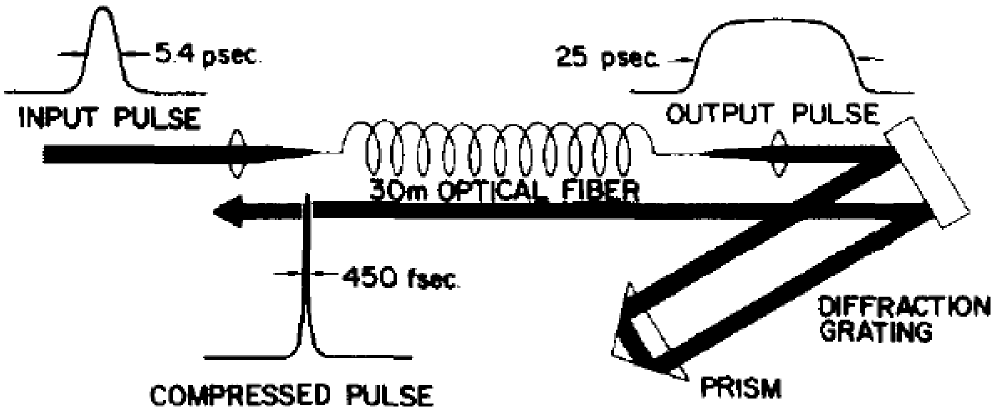


FIG. 1. Optical pulse compressor.

optical Kerr effect:

$$n = n_0 + n_2 I$$

$$\phi(x,t) = knx - \omega t = k[n_0 + n_2 I(t)]x - \omega t$$

Fast phase modulation increases pulse bandwidth.

B. Nikolaus and D. Grischkowsky, Applied Physics Letters **42**, 1 (1983)

Chirped pulse amplification with self-phase modulated pulse

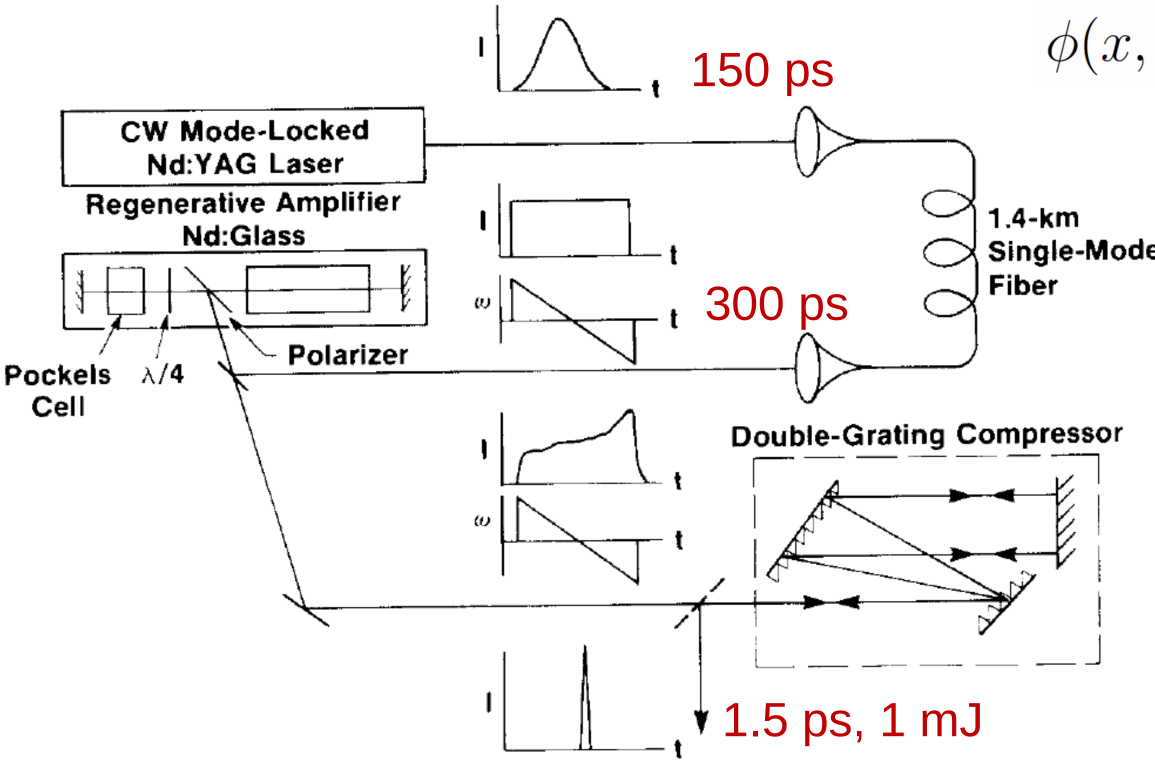


Fig. 1. Amplifier and compression system configuration.

$$
\begin{aligned}
\phi(x,t) &= knx - \omega t \\
&= k[n_0 + n_2 I(t)]x - \omega t
\end{aligned}
$$

Fast phase modulation increases pulse bandwidth.

D. Strickland and G. Mourou, Compression of amplified chirped optical pulses, Optics Communication **56**, 219 (1985)

Applications of Intense Lasers

- Coherent extreme-UV and soft x-ray sources
- Laser wakefield electron accelerator and x-ray generation
- Laser proton accelerator and neutron beam
- Laboratory astrophysics
- Perturbing the vacuum

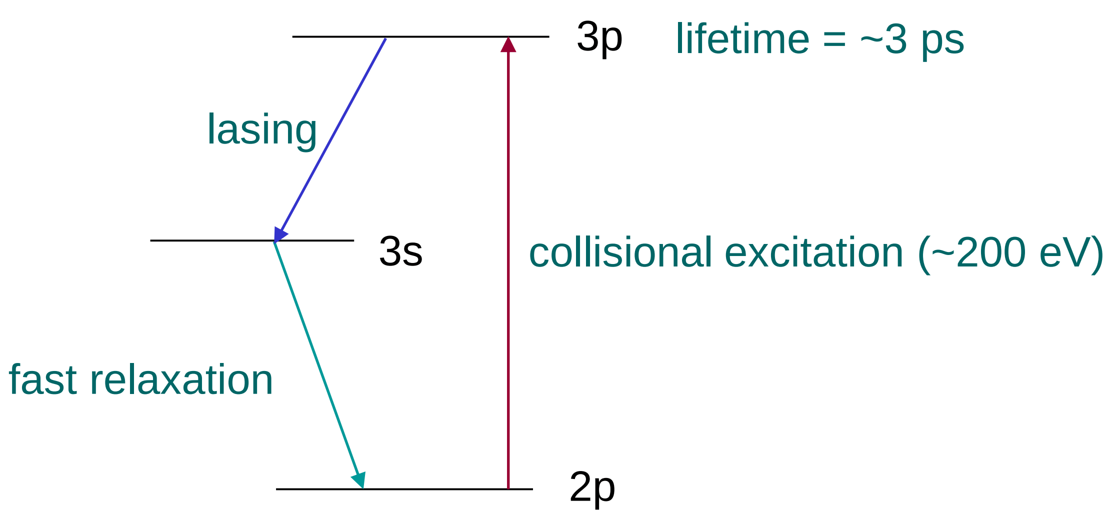
Coherent extreme-UV and soft x-ray sources

Converting electron energy to photon energy
in atoms

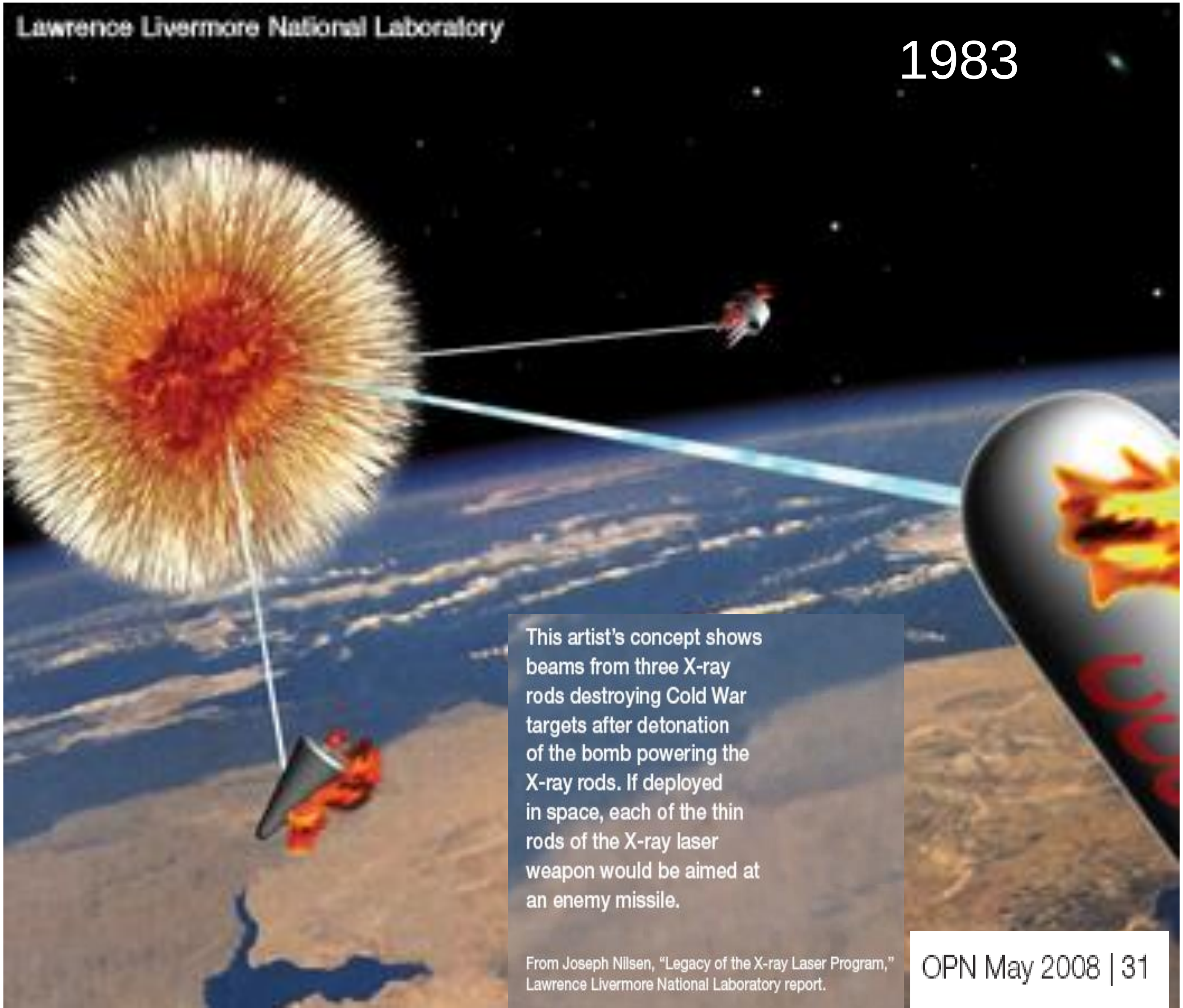
Energy levels of EUV lasers

He-Ne laser

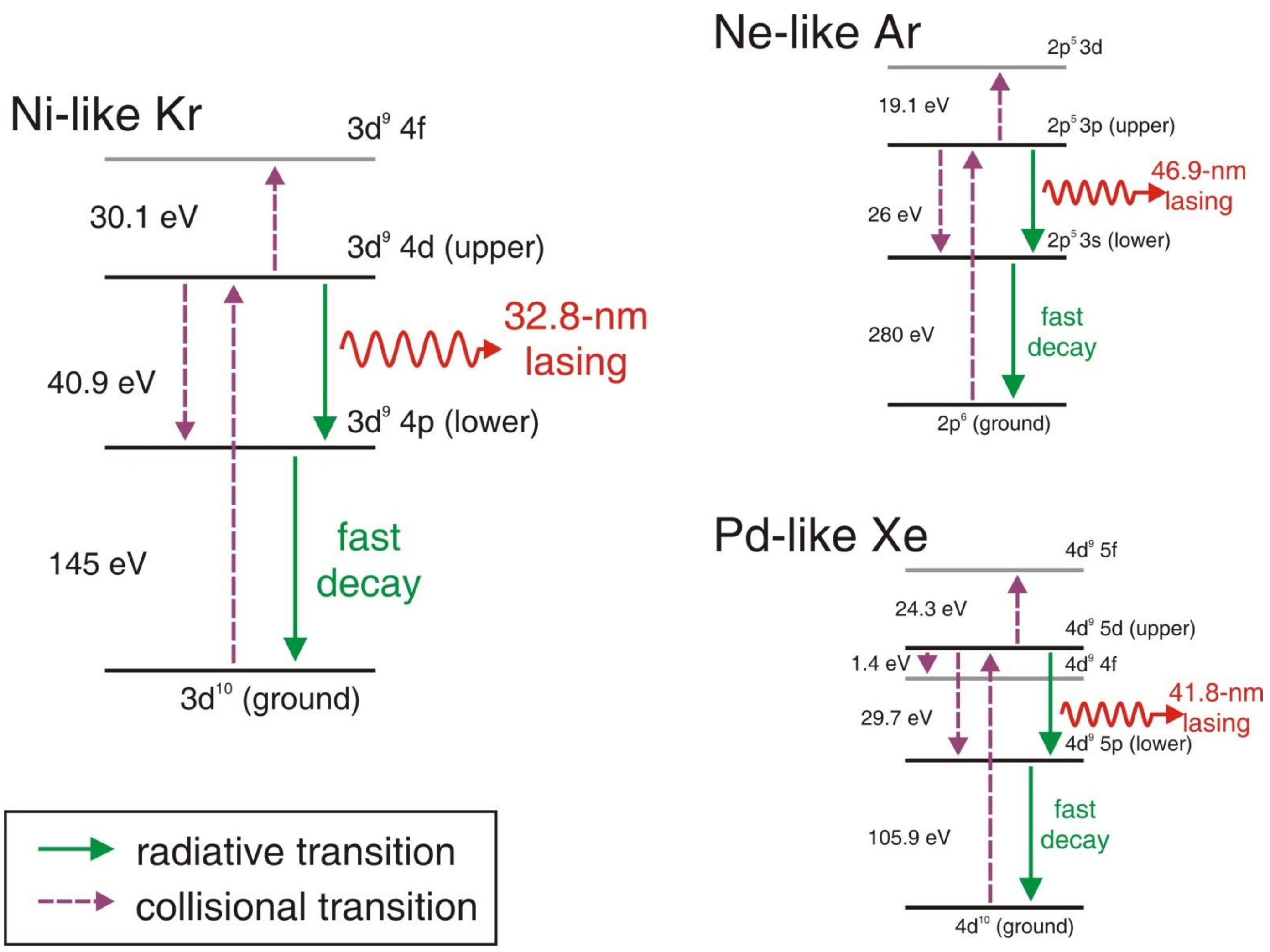
Ne-like ions: Ar^{8+}, Ti^{12+}, Fe^{16+}



X-ray lasers powered by nuclear bomb for "Star Wars"

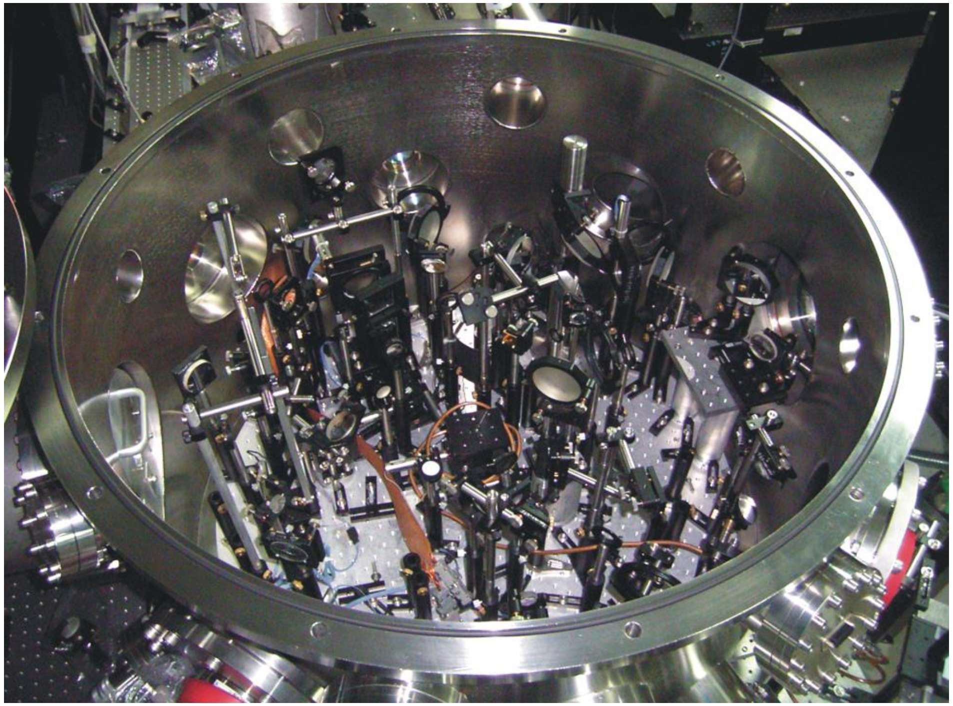


Energy levels of EUV lasers



Gas-target EUV laser

6 μJ/pulse   wavelength = 32.8 nm

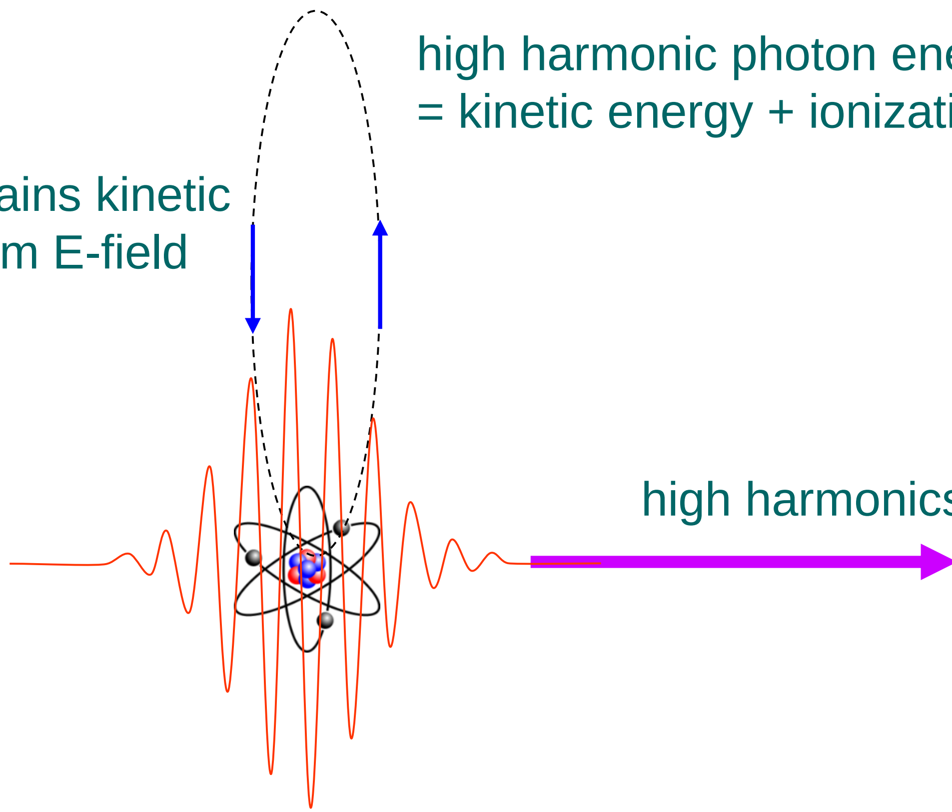


The single-pass gain is so large that stimulated emission overwhelms spontaneous emission without a laser cavity.

Phys. Rev. Lett. **99**, 063904 (2007)

Applied Physics B **105**, s00340 (2011)

High harmonic generation in intense laser field



The bandwidth is so large that it can be compressed to attosecond (10^{-18} s) pulses.

Laser wakefield electron accelerator and x-ray generation

Converting laser energy to electron energy
in plasmas

The 27-km ring accelerator at CERN

material break-down limit of conventional accelerator: MeV/cm

https://www.aps.org/publications/apsnews/201409/backpage.cfm

Importance of accelerator technology

Physics Today **65**(6), 8 (2012)

The future of particle physics depends on innovations in accelerator science. We need to invest in high-gradient acceleration technologies, including laser and plasma acceleration, that may be a key to building smaller, cheaper, more powerful accelerators.

Persis S. Drell

Director of SLAC

Proposal of laser-plasma accelerator (39 years ago)

NUMBER 4 PHYSICAL REVIEW LETTERS 23

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

1 GeV/cm vs. 200 keV/cm

Discovery of the "bubble regime"

A. PUKHOV[1,✉]
J. MEYER-TER-VEHN[2]

Laser wake field acceleration: the highly non-linear broken-wave regime

[1] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

ABSTRACT We use three-dimensional particle-in-cell simulations to study laser wake field acceleration (LWFA) at highly relativistic laser intensities. We observe ultra-short electron bunches emerging from laser wake fields driven above the wave-breaking threshold by few-cycle laser pulses shorter than the plasma wavelength. We find a new regime in which the laser wake takes the shape of a solitary plasma cavity. It traps background electrons continuously and accelerates them. We show that 12-J, 33-fs laser pulses may produce bunches of 3×10^{10} electrons with energy sharply peaked around 300 MeV. These electrons emerge as low-emittance beams from plasma layers just 700-μm thick. We also address a regime intermediate between direct laser acceleration and LWFA, when the laser-pulse duration is comparable with the plasma period.

Appl. Phys. B **74**, 355 (2002)

27 years after the proposal

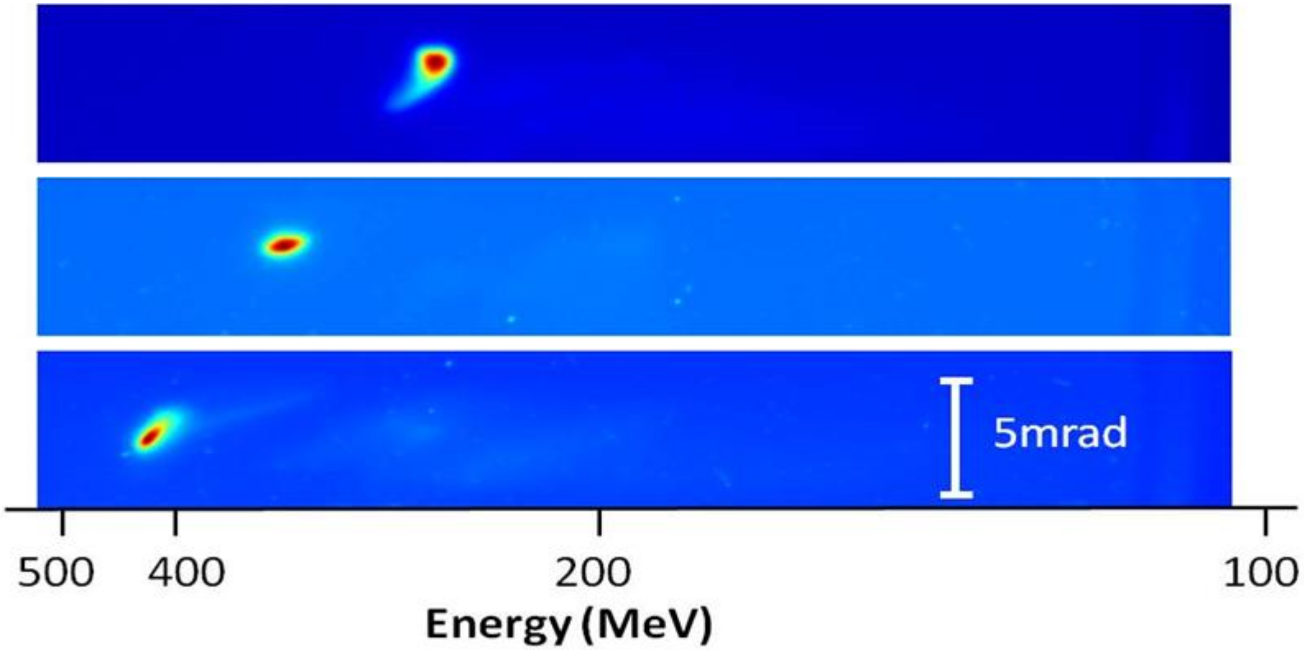
Published online: 24 September 2006; doi:10.1038/nphys418

Gigaelectron volt (GeV) electron accelerators are essential to synchrotron radiation facilities and free-electron lasers, and as modules for high-energy particle physics. Radiofrequency-based accelerators are limited to relatively low accelerating fields (10–50 MV m^{-1}), requiring tens to hundreds of metres to reach the multi-GeV beam energies needed to drive radiation sources, and many kilometres to generate particle energies of interest to high-energy physics. Laser-wakefield accelerators[1,2] produce electric fields of the order 10–100 GV m^{-1} enabling compact devices. Previously, the required laser intensity was not maintained over the distance needed to reach GeV energies, and hence acceleration was limited to the 100 MeV scale[3–5]. Contrary to predictions that petawatt-class lasers would be needed to reach GeV energies[6,7], here we demonstrate production of a high-quality electron beam with 1 GeV energy by channelling a 40 TW peak-power laser pulse in a 3.3-cm-long gas-filled capillary discharge waveguide[8,9].

2.5% r.m.s. energy spread, 1.6 mrad divergence r.m.s., ~30 pC

Electron acceleration with low energy spread

laser beam guided by self-focusing in a 4-mm helium jet



electron energy: 300-430 MeV

energy spread: 2-5%

laser energy and intensity: 1.7J, 50TW

35 years after the proposal

Selected for a Viewpoint in *Physics*

PRL **113,** 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

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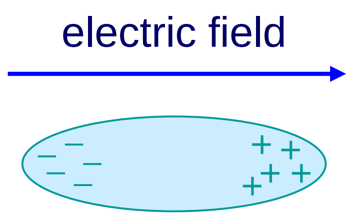
Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}\ \mathrm{cm}^{-3}$, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. A detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.

Ponderomotive force and optical tweezer

Invented by Arthur Ashkin, Nobel prize in physics 2018

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = f(t) \longrightarrow \tilde{x}(\omega) = \frac{\tilde{f}(\omega)}{-\omega^2 + i\gamma\omega + \omega_0^2}$$

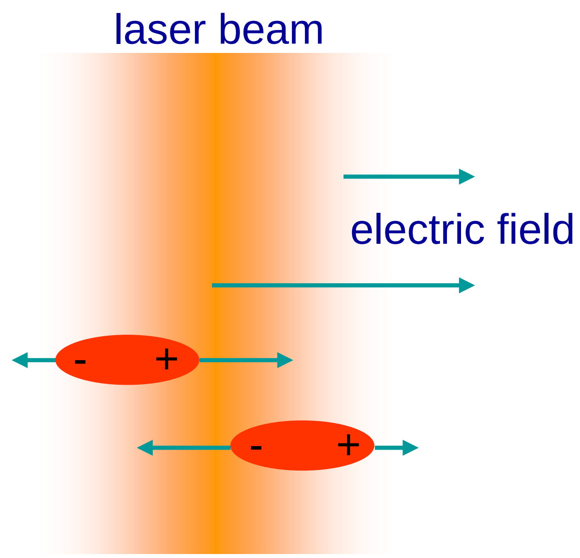


force on dipole $\mathbf{F} = (\mathbf{p}\cdot\nabla)\mathbf{E}$

induced dipole $\mathbf{p} \propto \mathbf{E}$

$$(\mathbf{p}\cdot\nabla\mathbf{E}) \propto \frac{1}{2}\nabla(\mathbf{E}\cdot\mathbf{E})$$

ponderomotive potential $U \propto -\frac{1}{2}(\mathbf{E}\cdot\mathbf{E})$



optical tweezer

Ponderomotive force for free electrons

$$\mathbf{a} = -\frac{e\mathbf{E}}{m}$$ nonrelativistic, ignoring $\frac{\mathbf{v}}{c} \times \mathbf{B}$

electron displacement $$\mathbf{x} = \frac{e\mathbf{E}}{m\omega^2}$$

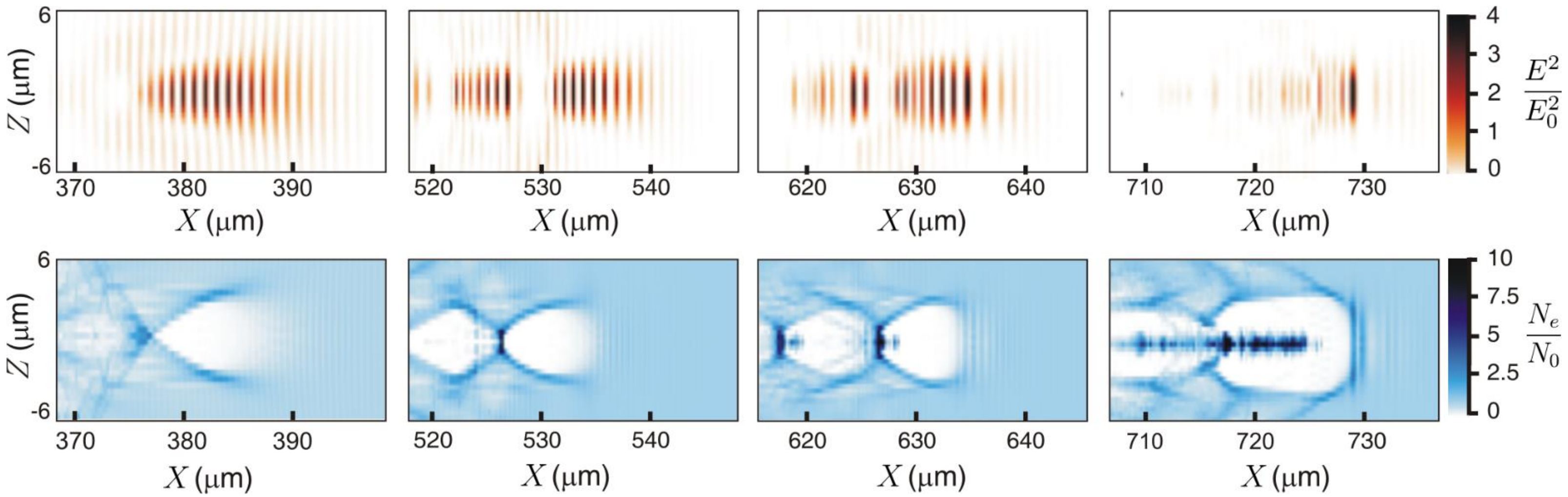
dipole moment $$\mathbf{p} = -\frac{e^2\mathbf{E}}{m\omega^2}$$

ponderomotive potential $$U = \frac{e^2}{2m\omega^2}\nabla(\mathbf{E}\cdot\mathbf{E})$$

An intense laser pulse expels electrons with a ponderomotive force of ~GeV/cm.

Acceleration in a nonlinear wake

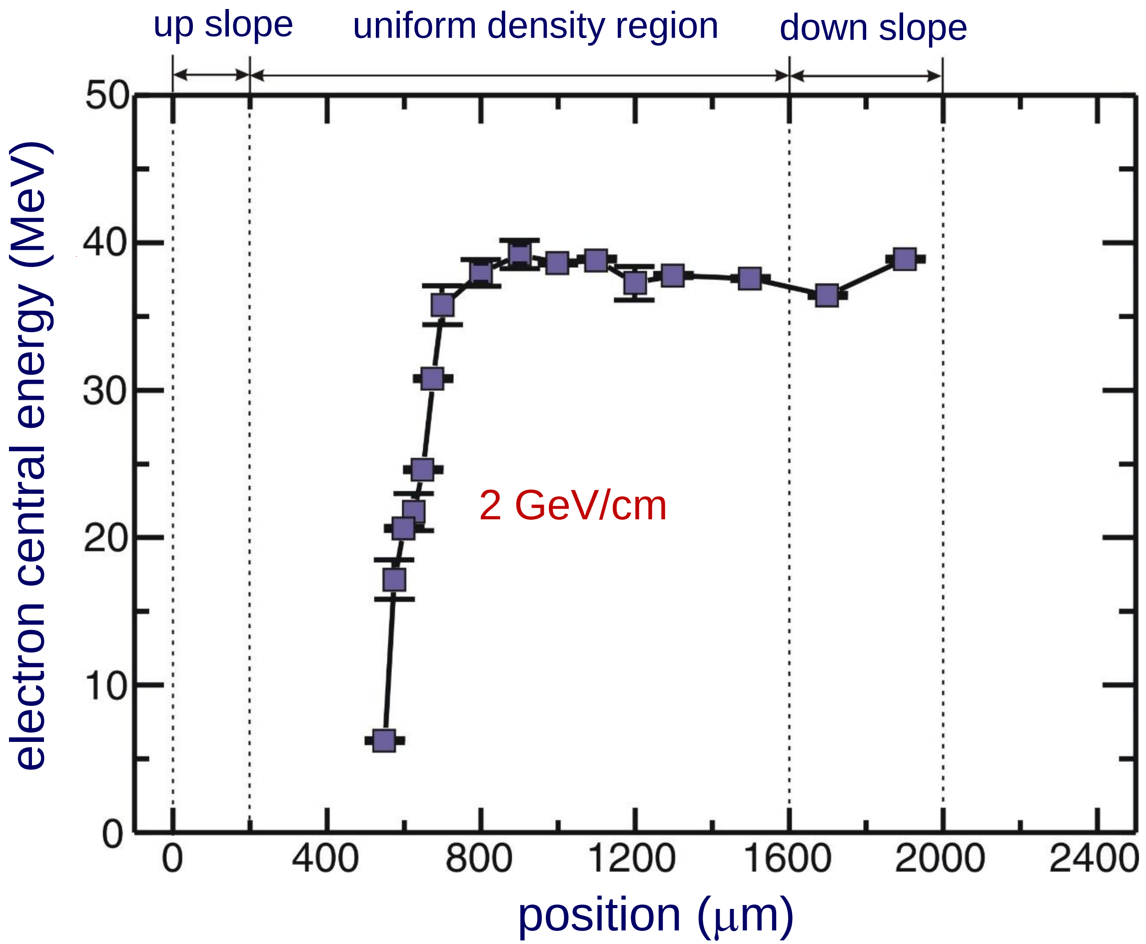
evolution of laser pulse



evolution of electron density

- After nonlinear propagation, the laser pulse becomes spatially self-focused and temporally compressed.
- The ponderomotive force expels electrons, resulting in a positively charged cavity following laser pulse.
- The electric field at the rear edge of the cavity is ~3×10^{11} V/m.

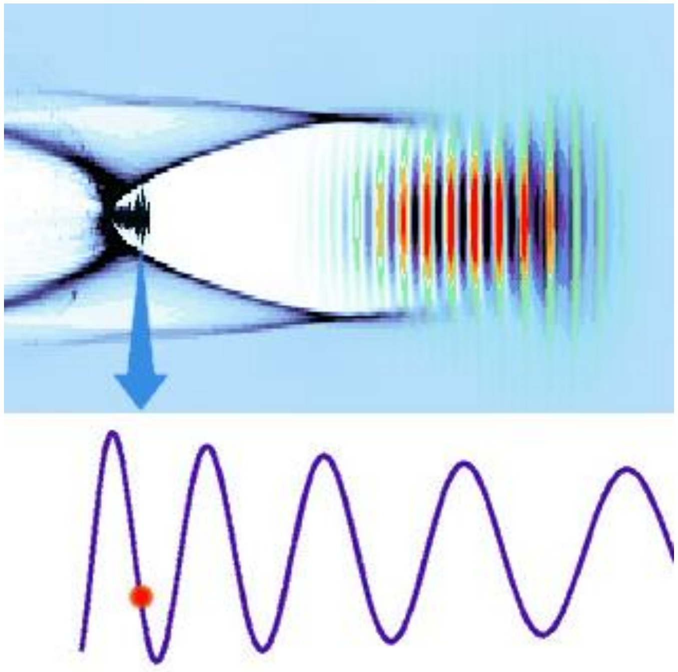
Resolving the acceleration process



- Saturation of electron energy occurs at ~200-μm acceleration distance.
- The first direct measurement of the acceleration gradient (~2 GeV/cm).

Phys. Rev. E **75**, 036402 (2007)

Generation of x-ray by betatron oscillation



electrons oscillating in the wakefield

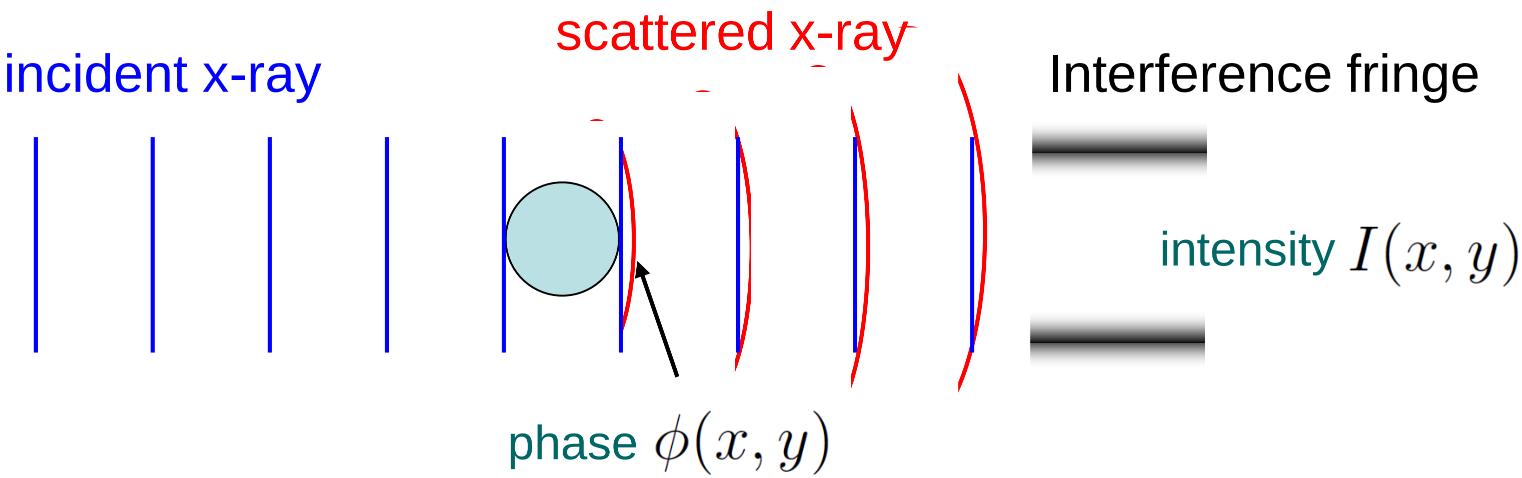
- Femtosecond exposure
- Micrometer source size
- High peak brilliance
- Broad spectrum

- Low average photon flux
- Shot-to-shot fluctuations

Rousse et al. Phys. Rev. Lett. **93**, 135005 (2004)

S. Corde et al. Rev. Mod. Phys. **85**, 1–48 (2013)

Principle of phase contrast imaging



$$I(x,y) \approx 1 + \frac{\lambda z}{2\pi}\nabla^2\phi(x,y)$$

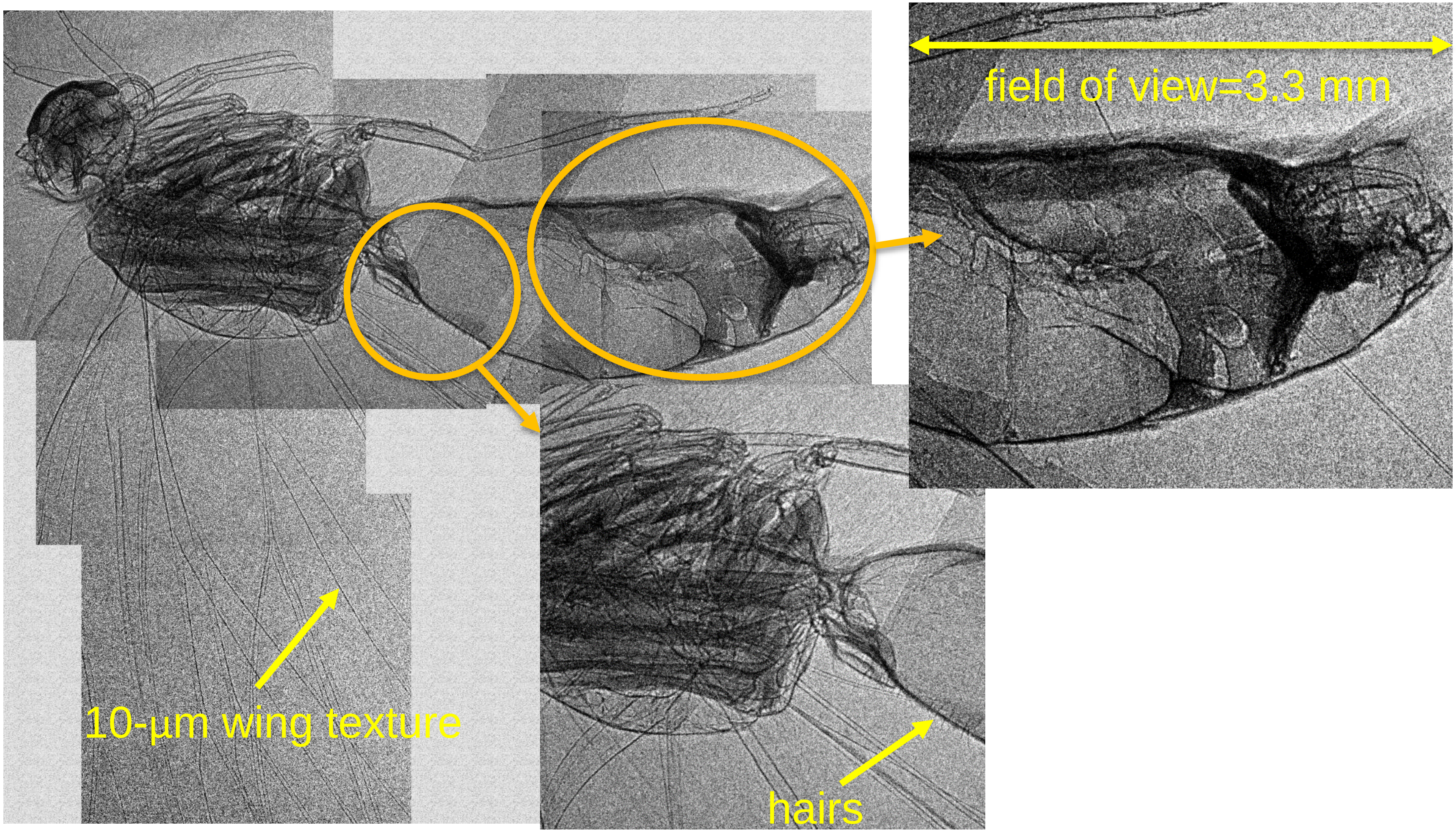
Source requirement:

- Small source size for high resolution
- Short temporal coherence length to avoid multiple fringes

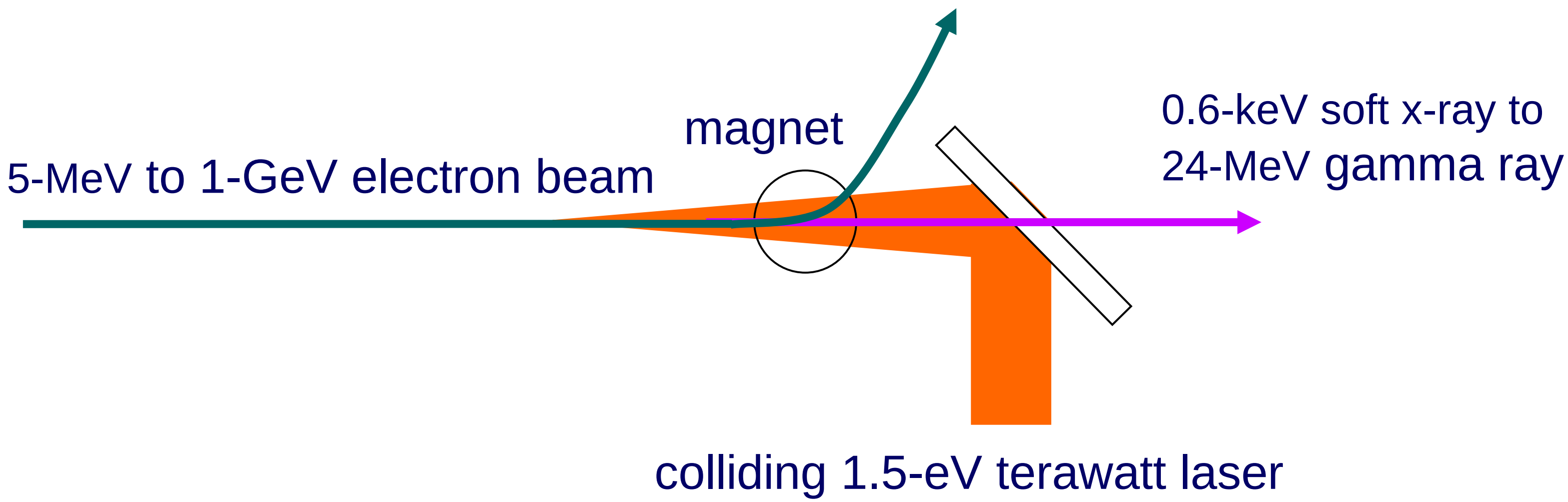
A. Pogany, D. Gao and S. W. Wilkins, Rev. Sci. Instrum. 68, 2774 (1997)

Phase contrast image of a butterfly

10-shot accumulated



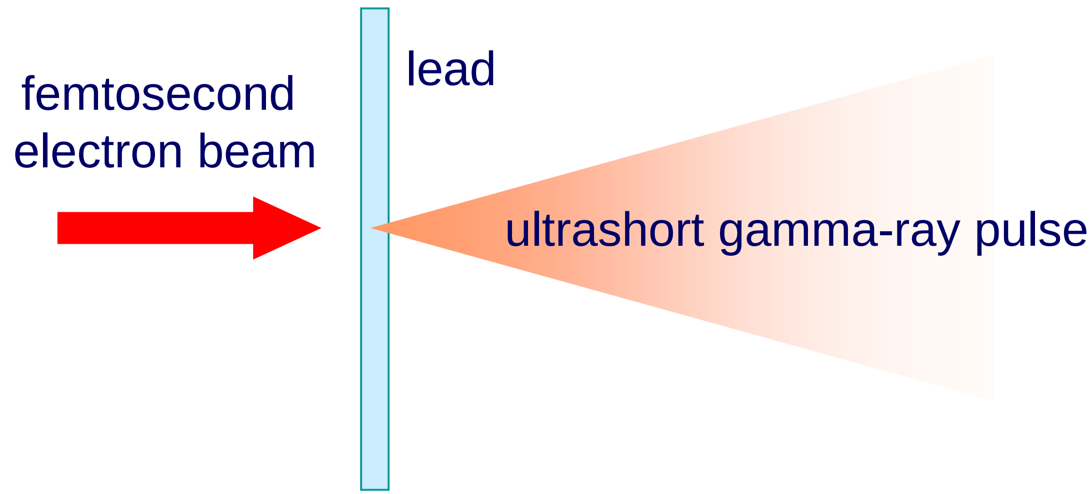
Single isolated soft x-ray to gamma-ray pulse

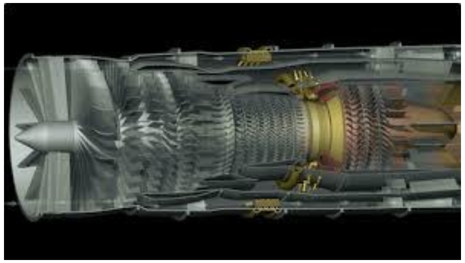


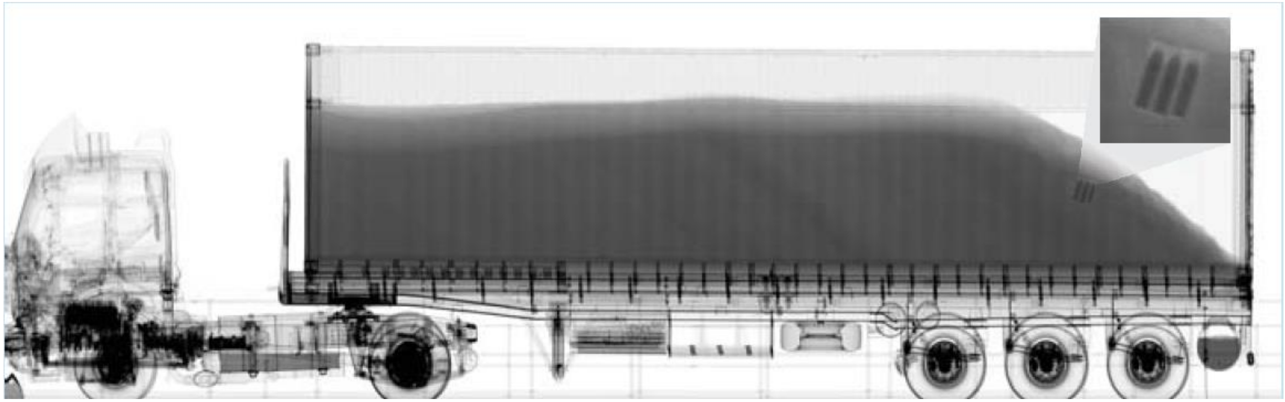
Theoretical estimation:

With 0.1-nC electron beam and 400-mJ laser beam, 10^9 double-Doppler boosted photons can be produced.

Ultrafast gamma-ray camera





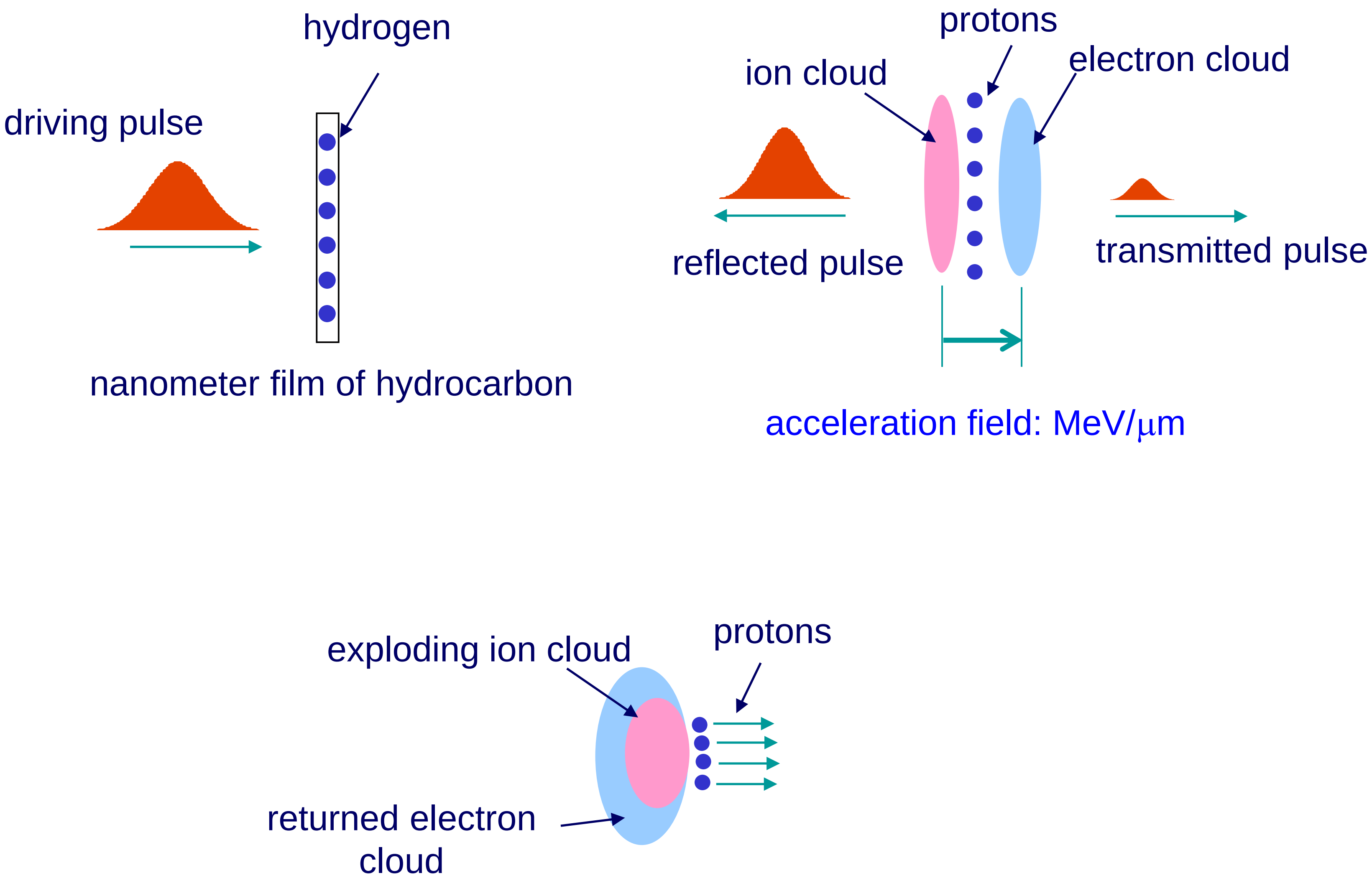


picture source: Physics Today **64**(6), 46 (2011)

Laser proton accelerator and neutron beam

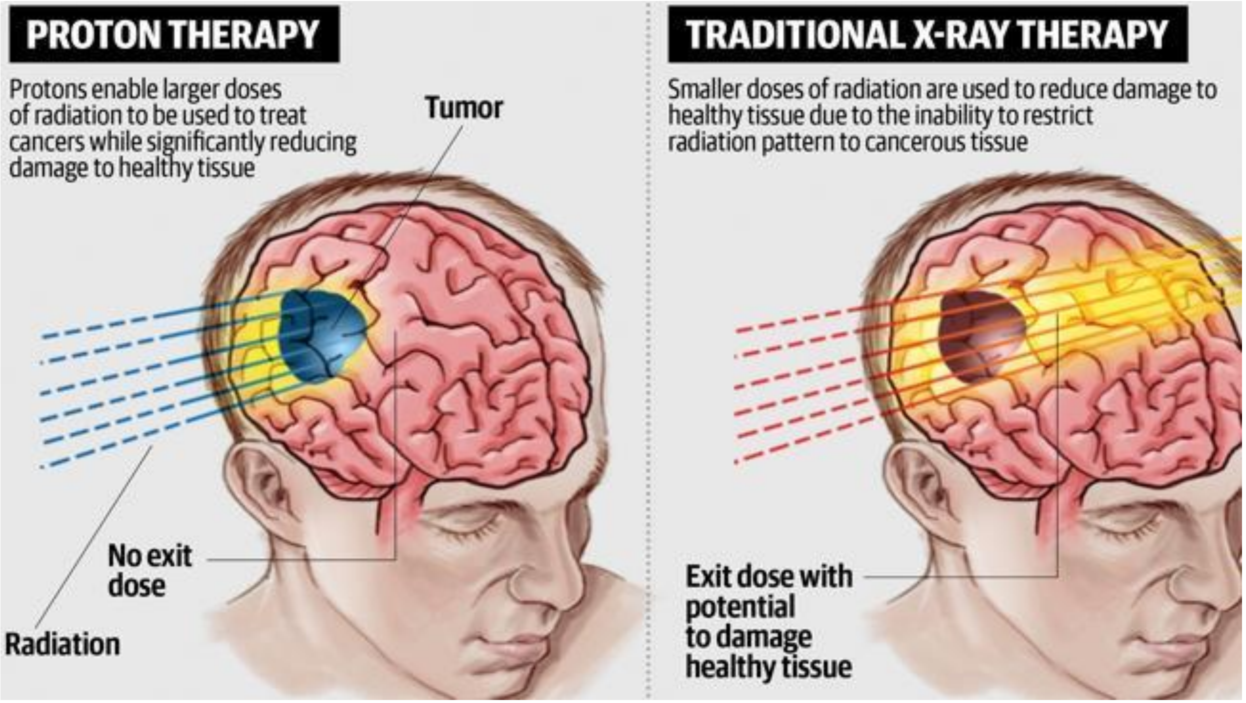
Photons push electrons, electrons pull protons

A scheme of laser-driven proton accelerator



New Journal of Physics **15**, 025026 (2013)

Proton therapy

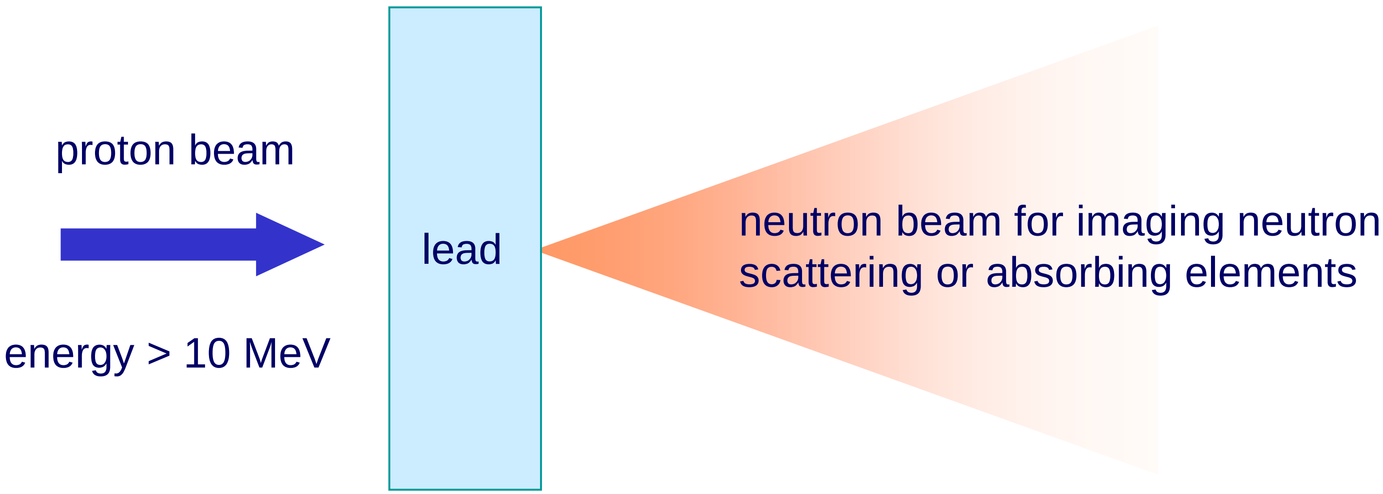


collateral damage

- Gamma ray: large
- Electron (250 MeV): medium
- Proton: small

picture source: http://www.dailytelegraph.com.au/news/nsw/proton-therapy-the-new-weapon-of-choice-against-cancer-is-coming-to-australia/story-fni0cx12-1227063925940

Pulsed spallation neutron source



conversion efficiency $\approx 4 \times 10^{-3}$

detection of plastic explosives

^{14}N + neutron $\longrightarrow$ $^{15}N + \gamma(10.8\ \mathrm{MeV})$

New Journal of Physics **7,** 253 (2005)

Nuclear Instruments and Methods in Physics Research A **353**, 635 (1994).

Assisting proton-boron fusion

ARTICLE

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Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

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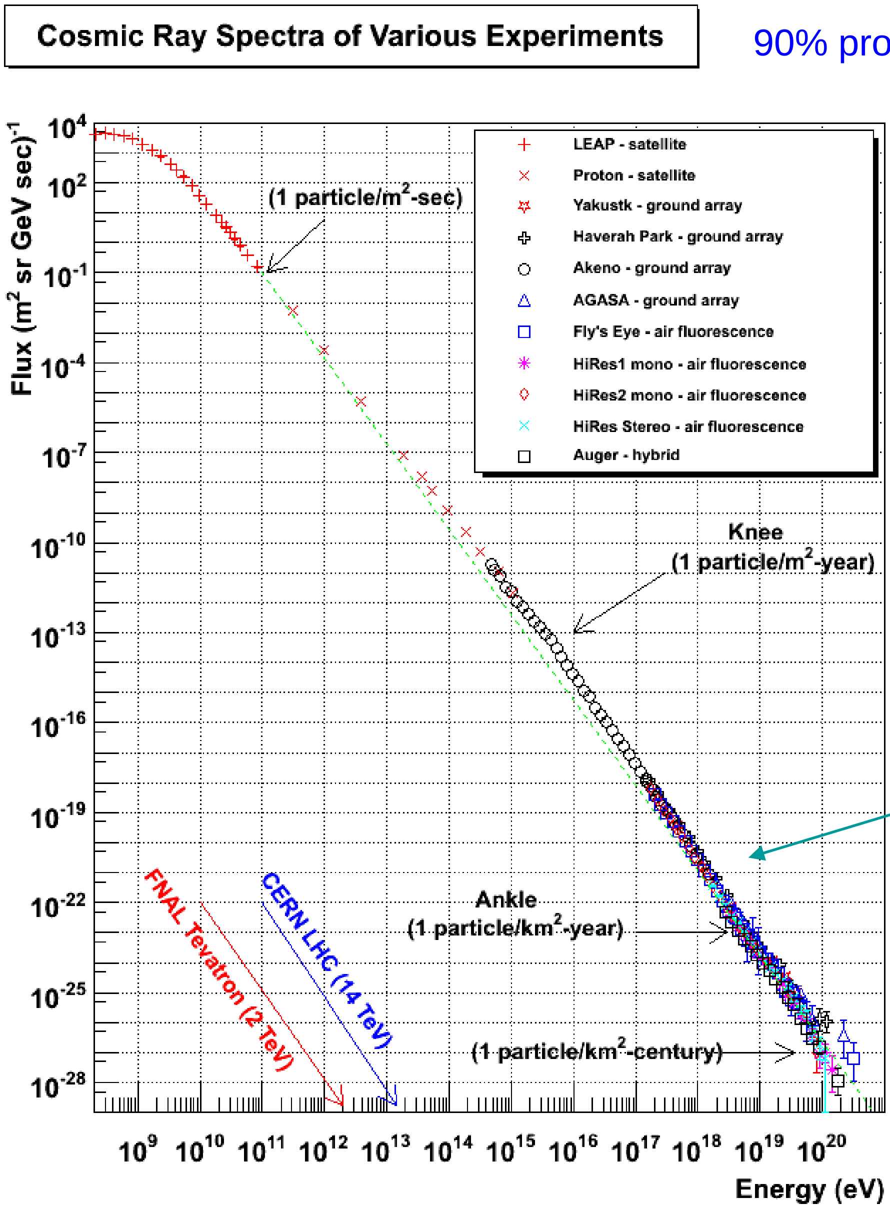
$$^{1}p + {}^{11}B + 0.6\,\text{MeV} \longrightarrow 3\ {}^{4}He + 8.7\,\text{MeV}$$

The advent of high-intensity-pulsed laser technology enables the generation of extreme states of matter under conditions that are far from thermal equilibrium. This in turn could enable different approaches to generating energy from nuclear fusion. Relaxing the equilibrium requirement could widen the range of isotopes used in fusion fuels permitting cleaner and less hazardous reactions that do not produce high-energy neutrons. Here we propose and implement a means to drive fusion reactions between protons and boron-11 nuclei by colliding a laser-accelerated proton beam with a laser-generated boron plasma. We report proton-boron reaction rates that are orders of magnitude higher than those reported previously. Beyond fusion, our approach demonstrates a new means for exploring low-energy nuclear reactions such as those that occur in astrophysical plasmas and related environments.

Laboratory investigation on the random-wave acceleration model of cosmic ray

Observed energy spectrum of cosmic ray

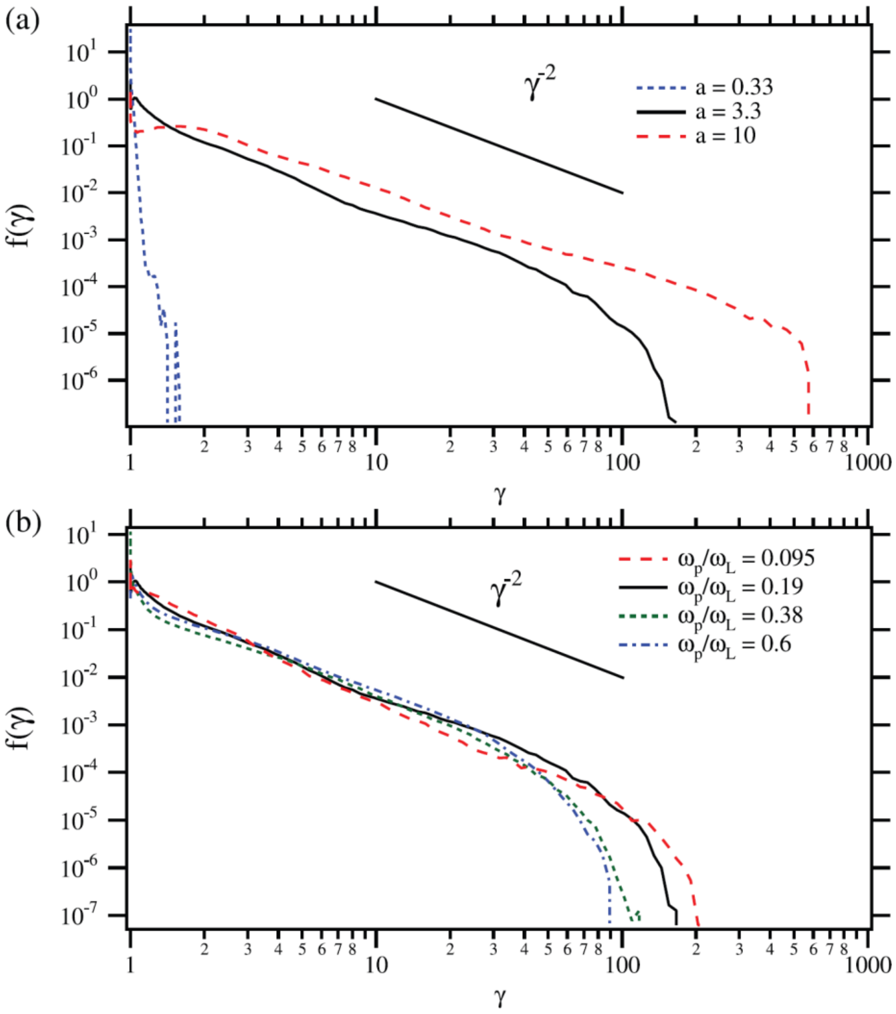


90% proton and 9% alpha particle

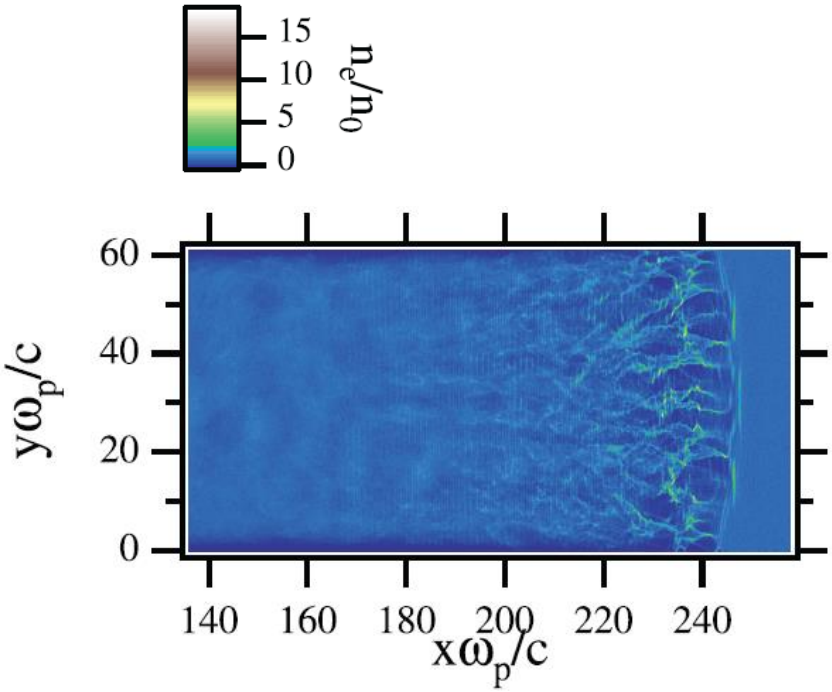
number slope ≈ $\gamma^{-2.2}$

http://www.physics.utah.edu/~whanlon/spectrum.html

Simulation of electrons accelerated by random waves

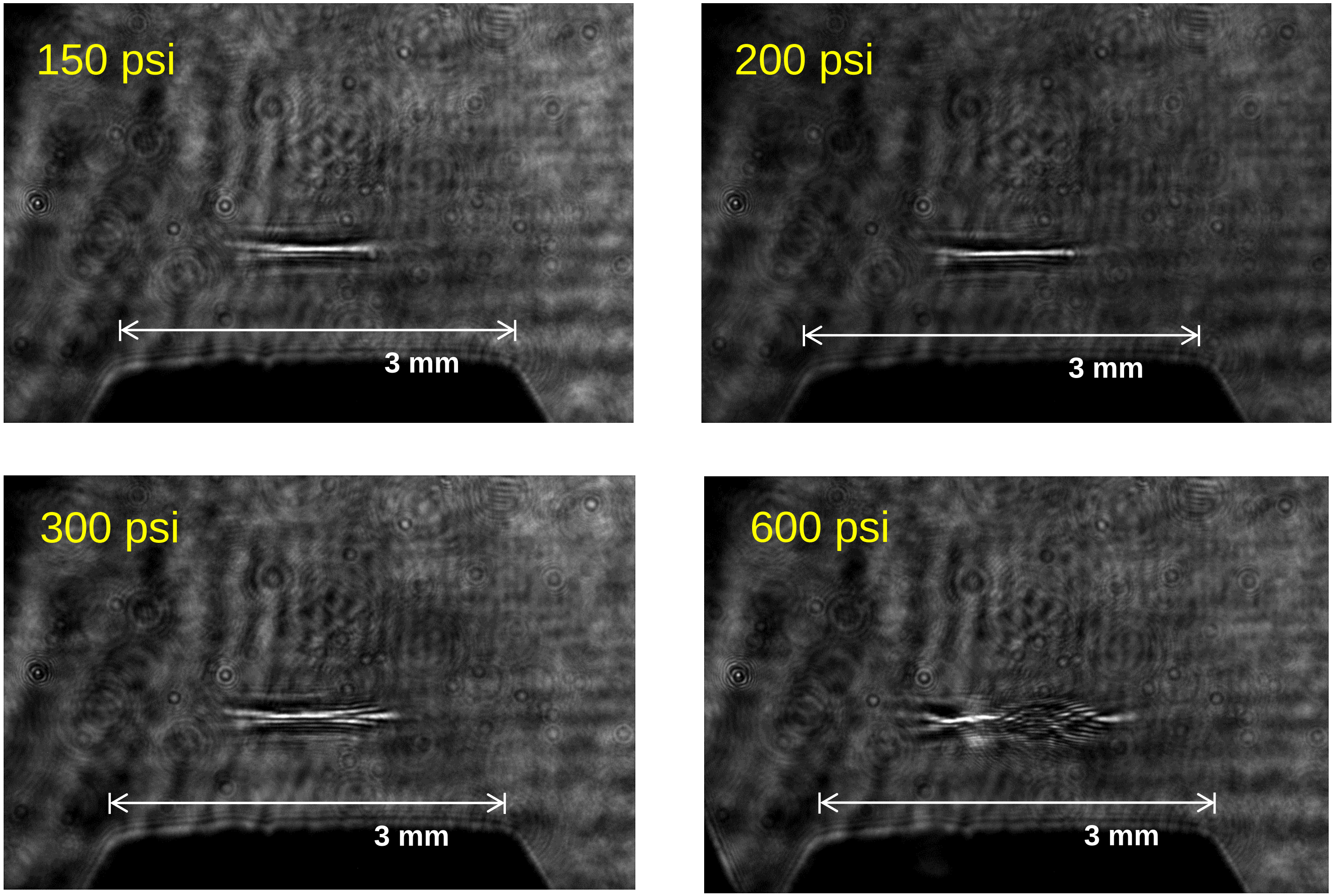


observed scaling law of cosmic ray ≈ $\gamma^{-2.2}$

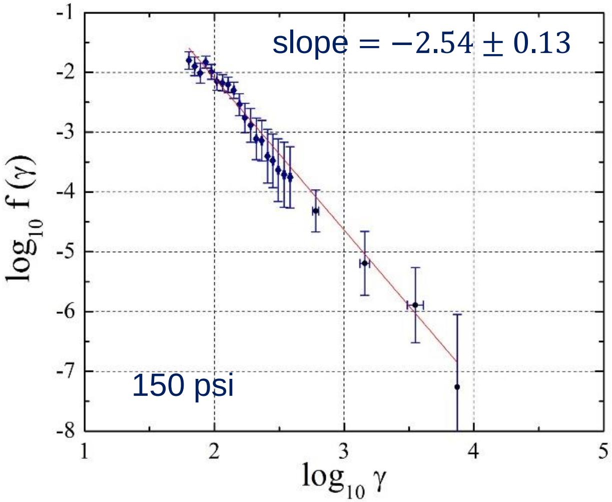


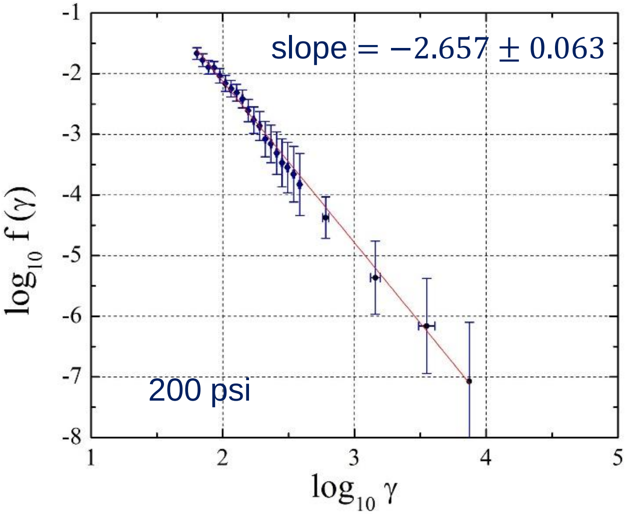
Y. Kuramitsu et al., Astrophys. J. Lett. **682**, L113 (2008)

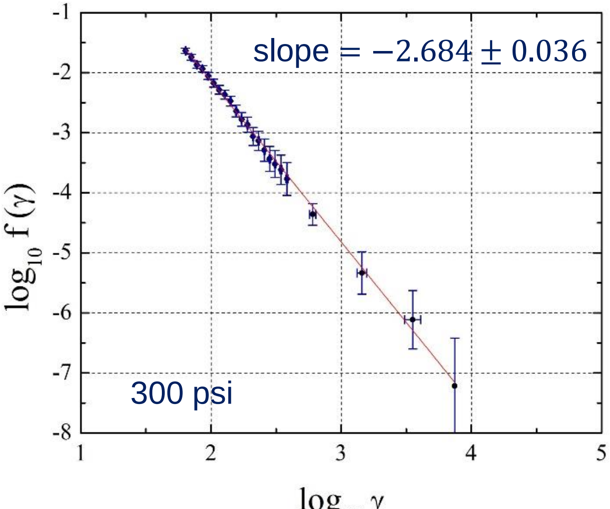
Shadowgrams of random wakes

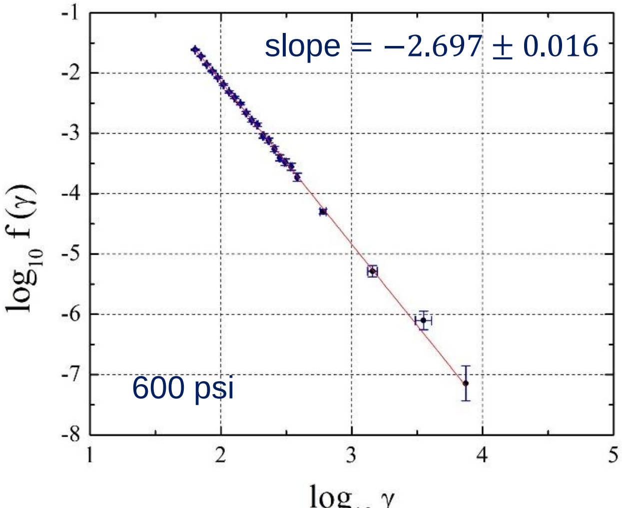


Electron energy spectrum









Perturbing the vacuum

Vacuum can breakdown under intense field

Vacuum birefringence due to virtual e^+e^- pairs

On the observation of vacuum birefringence

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Abstract

We suggest an experiment to observe vacuum birefringence induced by intense laser fields. A high-intensity laser pulse is focused to ultra-relativistic intensity and polarizes the vacuum which then acts like a birefringent medium. The latter is probed by a linearly polarized X-ray pulse. We calculate the resulting ellipticity signal within strong-field QED assuming Gaussian beams. The laser technology required for detecting the signal will be available within the next three years.

Requires a petawatt laser and a synchronized hard x-ray pulse.

Opt. Comm. **267**, 318 (2006)

Summary

- A simple idea borrowed from popular radar technology increased laser power by four orders of magnitude.
- It generated a broad frontier of fundamental research and futuristic applications.
- 30 years are needed to develop a promising idea to full recognition.

100-TW laser lab at NCU

Thank you for your attention!