2443-1

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

4 - 15 February 2013

Historical Remarks on Laser Science and Applications

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Historical Remarks on Laser Science and Applications

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International Center for Theoretical Physics
Winter College on Optics
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Some Anniversary Dates

- **May 16, 1960:**
  First laser action achieved by Theodore H. Maiman (Ruby Laser). Beginning of laser era

- **August 1961 :**
  First observation of optical harmonic generation (Peter Franken). Beginning of nonlinear optics

- **1962:**
  First semiconductor laser (R.N. Hall). Beginning of, possibly, the most important laser

- **1965:**
  First ultrashort-pulse generation (A.J. DeMaria). Beginning of ultrafast optical sciences

Plan of this Talk 1

- A prologue: the race to make the first laser
- The invention of the ruby laser
- The invention of the semiconductor laser
- Early developments in laser science (1960-1970)
- The birth of nonlinear optics

Very coarse review of some of most important achievements with a few anedocts and curiosities

Plan of this Talk 2

- A bridge between nonlinear optics and laser physics:

  ultrafast laser science

- A bridge between high-resolution spectrosocpy and ultrafast lasers: The frequency comb

- Historical remarks on Nobel Prizes

- Early developments in laser applications (1960-1970)

- Conclusions

Very coarse review of some of most important points with a few anedocts and curiosities

A prologue :

The race to make the first laser

Starting of the Race

- Race started with Schawlow and Townes paper (middle 1958, i.e. 2 years before)

A.L. Schawlow and C.H. Townes *Infrared and Optical Masers* Phys. Rev. **112**, 1940 (1958)

- Several laboratories, mostly in U.S., involved
  Bell Labs, TRG, Columbia Un., IBM labs, Hughes, American Optical
  Lebedev Inst., Moscow Power Inst., Oxford Univ.

Jeff Hecht, *Beam: The Race to Make the Laser*, Oxford Univ. Press, Oxford 2005

A Strong Contender: Gordon Gould

- Graduate student at Columbia University
- October 1957: after talking with Townes, Gould asks a notary public to authenticate a first laboratory notebook (9 pages) containing several ideas about lasers
- August 1958: after receiving reprint of Schawlow and Townes paper, Gould asks a City College professor to sign (as read and understood) a second notebook (23 pages)

The Thirty-Year Patent War

- Two notebooks $\Rightarrow$ thirty-year patent war (particularly against Schawlow-Townes patent)
- After several defeats, Gould won his patent suit
- Gould the real inventor of the laser?
- The “legal” truth does not always coincide with the “scientific” truth (i.e. **Gould won where he deserved to lose**)

Curiosity: Gordon Gould went to work at TRG, which was awarded a millionaire grant to make a laser according to a proposal by Gould. Gould was however prevented to work on his own ideas, since researches were done at a classified area in TRG.

Nick Taylor *The inventor, the Nobel laureate and the thirty-year patent war*, An Authors Guild Backinprint.com Edition, 2000

Comments about Gordon Gould

- Inventor, with a lot of impressive ideas
- These ideas were not made available to the scientific community and did not have any influence on successive scientific developments
- Invented the name LASER

The Invention of the First Laser

The Ruby Laser

On May 16, 1960, first laser action was achieved by Theodore H. Maiman (Ruby Laser)

The scientific community was shocked: (a) The simplicity of the components used. (b) The 3-level nature of the laser transition. (c) The type of laser excitation (pulsed by a flashlamp)

Curiosity: T.H. Maiman, a young scientist at that time, won the race with a very limited investment by Hughes.

The Account of the Achievement

It was in the afternoon of May 16, 1960; it was time to confirm or deny all the fears of why the “ruby can’t work” or why “lasers can be made to work”. No more calculations, no more diversionary experiments. This was the moment of truth…We turned up the power supply to 500 volts. We fired the flashtube. Indeed, we observed a trace on the Memoscope! The trace was a recording of the red ruby fluorescence. The decay in the trace was about three milliseconds, the lifetime of the upper possible level…But when we got past 950 volts on the power supply, everything changed! The output trace started to shoot up in the peak intensity and the initial decay rapidly decreased. Voilà. This was it! The laser was born!

T. H. Maiman, *The Laser Odyssey*, Laser Press, Blaine, WA (2000) Chapt. 10

Th.H. Maiman Holding the first Laser

The History of Maimam Publication

- Physical Review Letters rejected his first publication (Optical Maser Action in Ruby)
- A paper with similar content accepted by Nature (6 Aug. issue)
- During the press release organized by Hughes in N.Y., more extensive paper was stolen and published on a not well known British Journal

T.H. Maiman, *Stimulated Optical Radiation in Ruby Masers*, Nature, **187**, 493 (1960)

T.H. Maiman, *Optical Maser Action in Ruby*, Brit. Comm. and Electr. 674 (1960)

The Press Release

July 7, 1960 New York

Not the true first laser! Immediately duplicated in many labs (TRG, IBM, **Bell Labs**)

Bell Labs and the Ruby Laser

- October 1960
  R.J. Collins, D.F. Nelson, A.L. Schawlow, W. Bond, C.G.B. Garrett, W. Kaiser
  Coherence, Narrowing, Directionality, and Relaxation Oscillations in the Light Emission from Ruby
  Phys. Rev. Letters **5**, 303 (1960)

The "wrong" laser was actually behaving better than the original one !

Was it Really Laser Action?

- A few authoritative people doubted about Maiman's results
  Large beam divergence
  Large spectra bandwidth
  Absence of laser spiking
- Indeed, on May 16 1960, Maiman did observe laser action of a special kind
- Anyway Maiman is to be celebrated as the creator of the first laser

Charles H. Townes, *How the Laser Happened*, Oxford University Press (New York, 1999)
D.F. Nelson, R.J. Collins and W. Kaiser, *Bell Labs and the Ruby Laser*, Phys. Today **63** 40 (2010)
T. H. Maiman, *The Laser Odyssey*, Laser Press, Blaine, WA (2000)

End of the Race (1960)

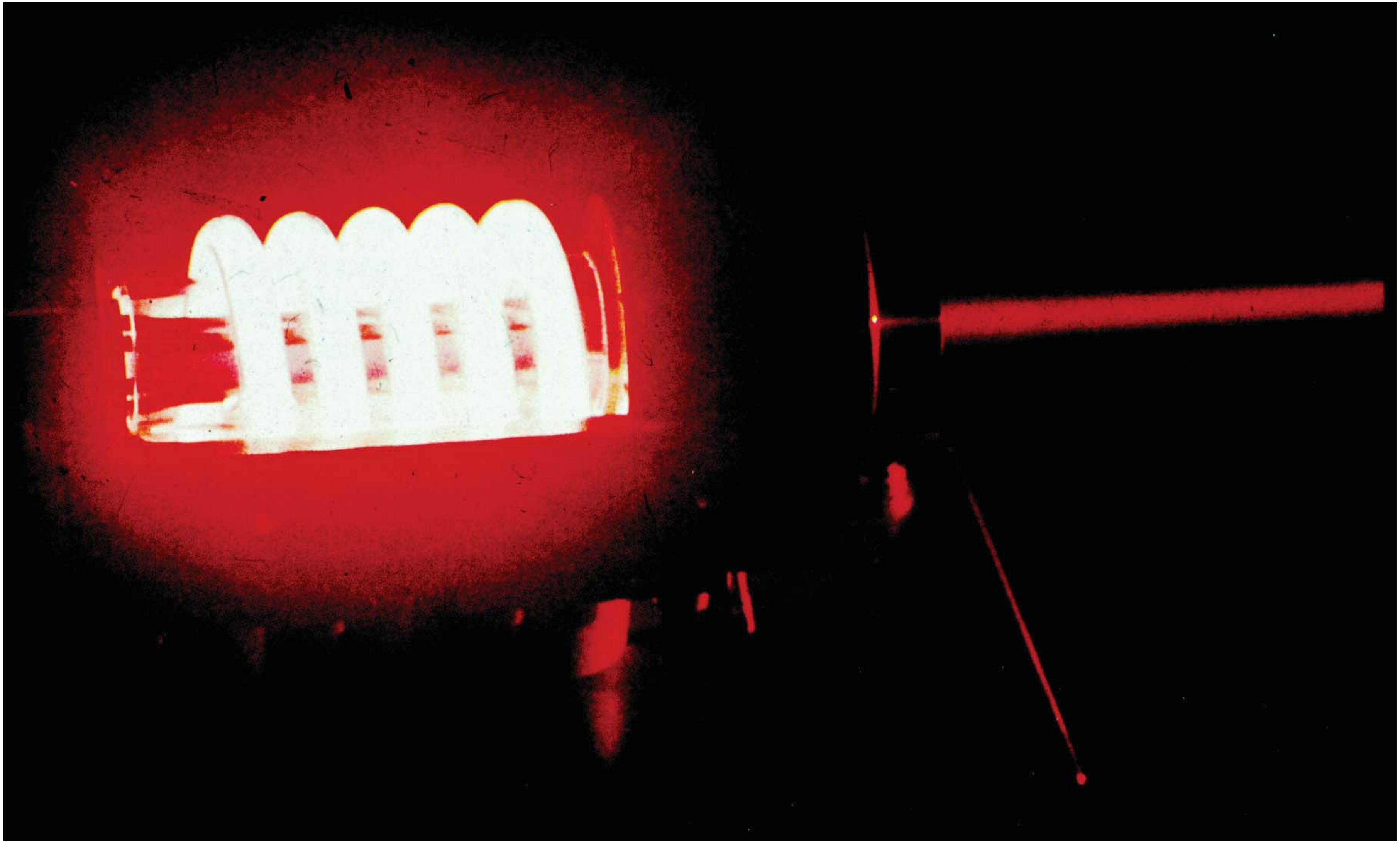
♦ May 16 1960:
First laser demonstration by Maiman (+ Bell Labs paper)

♦ A few months later:
P.P. Sorokin *et al.* $U^{3+}:CaF_2$ (2,5 μm) $Sm^{2+}:CaF_2$ (~700 nm) [4 level lasers, first rare-earth laser, cryogenic temperature]

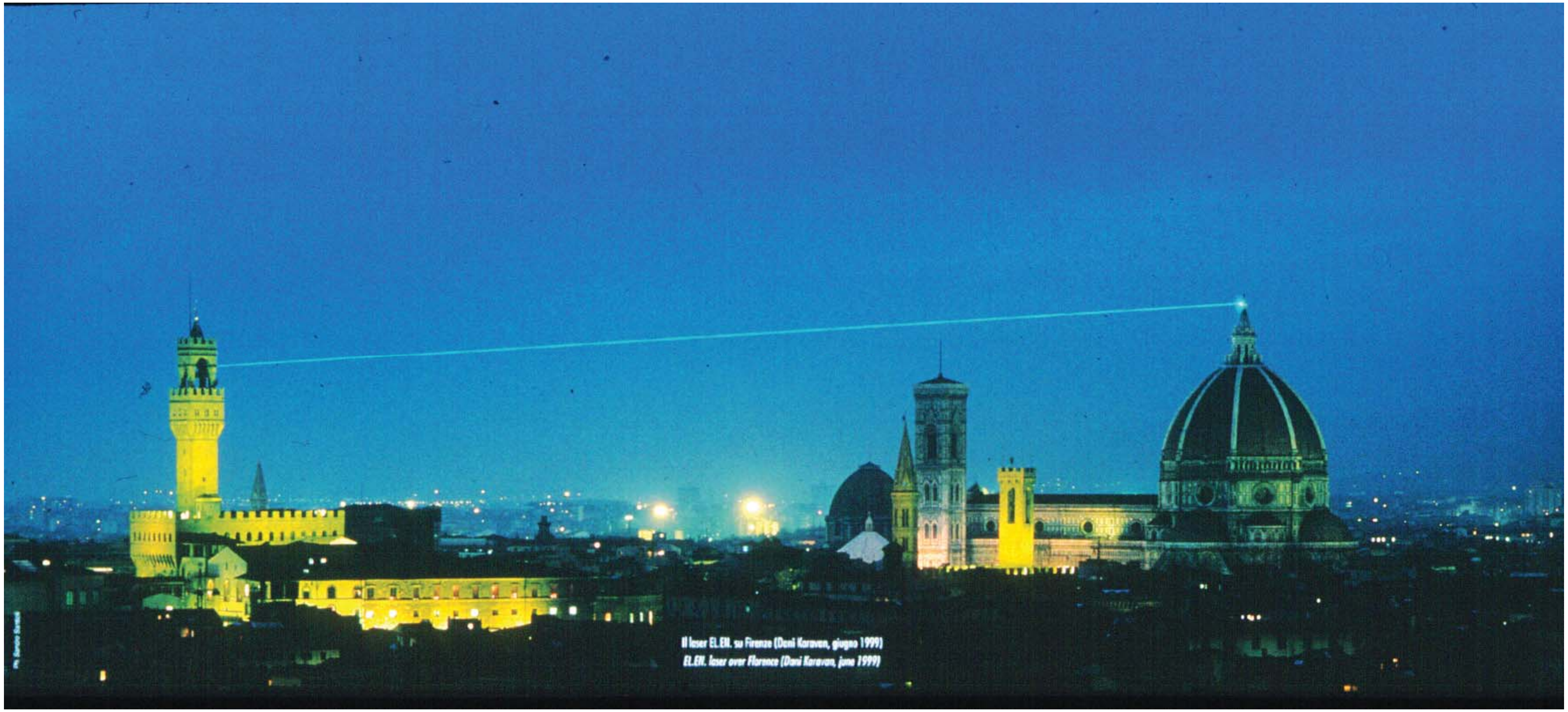
♦ December 1960:
A. Javan *et al.* He-Ne laser (1.15 μm); the first cw laser; the first gas laser; the first electrically excited

♦ By the end of 1960:
quite different types of lasers were operated ⇒ door open to all successive developments

The Working-Horse for Laser Physics



Directionality of a Laser Beam



The Invention of the Semiconductor Laser

The p-n Semiconductor Laser

- Invented almost simultaneously by four groups

  R.N. Hall *et al.*, *Coherent Light Emission from GaAs Junctions*, Phys. Rev. Letters, **9**, 366 (1962)

  M.I. Nathan *et. al*, *Stimulated Emission of Radiation from GaAs p-n Junctions*, Appl. Phys. Letters, **1**, 62 (1962)

  T.M. Quist *et al.*, *Semiconductor Maser of GaAs*, Appl. Phys. Letters, **1**, 91 (1962)

  N. Holonyak and S.F. Bevacqua, *Coherent (Visible) Light Emission from Ga($As_{1-x}P_x$) Junctions*, Appl. Phys. Letters, **1**, 82 (1962)

- p-n junction semiconductor laser are now a scientific curiosity

The Heterostructure Semiconductor Laser

- Proposed indipendently by H. Kroemer and Zh.I. Alferov in 1963

  H. Kroemer, *A Proposed Class of Hetero-Junction Laser*, Proc. IEEE, **51**, 1782 (1963)
  Zh. I. Alferov and R. F. Kazarinov, *Authors Certificate* N. 181737, *Claim* N. 950840, March 1963 [in Russian].

- First realization in 1970 mainly by Zh.I. Alferov

  Zh. I. Alferov *et al., Fiz. Tekh. Poluprov.*, **2**, 1545 (1968) [*Soviet Phys. – Semicond*. **2**, 289 (1969)]
  Zh. I. Alferov *et al.*, *Fiz. Tekh. Poluprov.*, **3**, 1328 (1969) [*Soviet Phys. – Semicond*. **3**, 1107 (1970)

Zh.I. Alferov e H. Kroemer shared one half of the Nobel Prize in Physics for year 2000

Early Developments in Laser Physics

(1960-1970)

A very Exciting Period

- Most important new lasers and phenomena related to physics of lasers (Relaxation Oscillations, Q-Switching, Mode-Locking, Single-mode oscillation)

- Most important phenomena related to laser-matter interaction (e.g nonlinear optics, high-resolution spectroscopy, ultrafast optical sciences)

Q-Switching

- Attributed to:

  R.W. Hellwarth, *Control of Fluorescent Pulsations* in Advances in Quantum Electronics, Columbia. Un. Press, N. Y. 1961, p.334

- Actually

  The idea of Q-switching was already contained in one of two notebooks of G. Gould $\Rightarrow$ He lost his patent suit against Hughes (the legal "truth" did not coincide with the scientific truth i.e. Gould lost where he deserved to win)

Q-Switching

- Realized by

  F.J. McClung and R.W. Hellwarth, *Giant Optical Pulsations from Ruby*

  J. Appl. Phys. **33**, 828 (1962)

- Curiosity: Accidental discovery of stimulated Raman scattering

  E.J. Woodbury and W.K. Ng, *Ruby Laser Operation in the near IR*

  Proc. IRE **50**, 2367 (1962)

Mode-Locking

- First demonstration of synchronous intracavity modulation:
  Karl Gürs, *Innere Modulation von optischen Masern*
  Z. für Physik, **172**, 163 (1963)
  L.E. Hargrove *et.al.*, Appl. Phys. Lett. **5**, 4 (1964)

- Explanation in terms of mode-locking
  M. DiDomenico, J. Appl. Plys. **35**, 2870 (1964)

- Passive ML of Q-switched lasers (picosecond pulses):
  H. W. Mocker and R.J. Collins, Appl. Phys. Lett. 7, 270 (1965)
  A.J. DeMaria *et. al*, Appl. Phys. Lett. 8, 174 (1966)

- Curiosity::
  Initial experiments performed for optical communications

The Birth of Nonlinear Optics

Second Harmonic Generation

♦ First discovery

P.A. Franken et al., *Generation of Optical Harmonics*
Phys. Rev. Lett. **7**, 118 (1961)

♦ The door to real-word applications

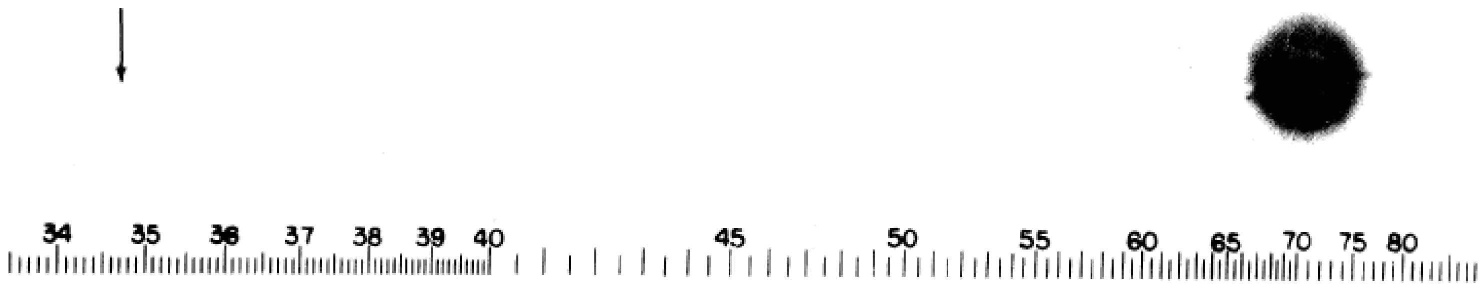
J.A. Giordmaine, *Mixing of Light Beams in Crystals*
Phy. Rev. Lett. **8**, 19 (1962)
P.D. Maker et al., *Effects of Dispersion and Focusing on the Production 0f Optical Harmonics*
Phy. Rev. Lett. **8**, 21 (1962)

The Peter Franken PRL Paper

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)



"…The arrow at 3472 A indicates the small but dense image produced by the second harmonic. The image of the primary beam at 6943 A is very large due to halation."

Stimulated Raman Scattering

- Accidentally discovered by Woodbury and Ng

(following demonstration of Q-switching by F.J. McClung and R.W. Hellwarth using a nitrobenzene filled Kerr cell)

E.J. Woodbury and W.K. Ng, *Ruby Laser Operation in the near IR,* Proc. IRE **50**, 2367 (1962)

- Understood as SRS by Eckhardt et al.

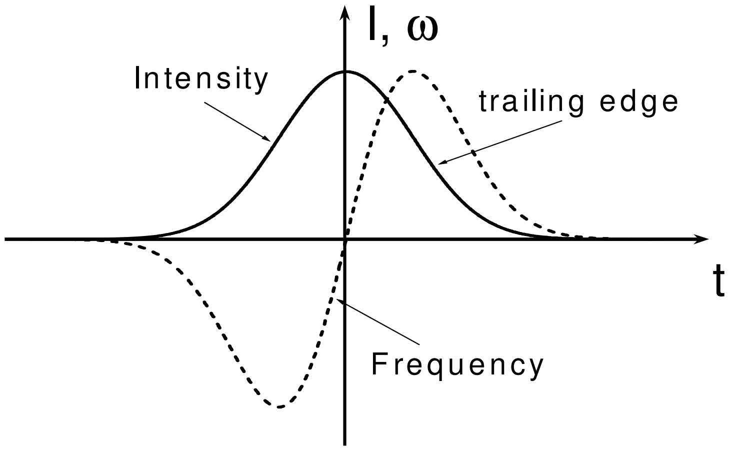
G. Eckhardt, R.W. Hellwarth *et al.*, *Stimulated Raman Scattering from Organic Liquids,* Phys. Rev. Letters **9**, 455 (1962)

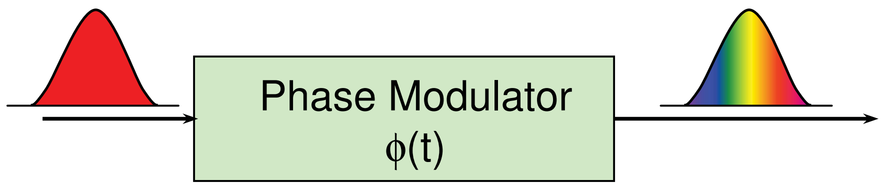
Self-Phase Modulation (SPM)

- Optical Kerr effect: $n(\mathbf{r},t) = n_0 + n_2\, I(\mathbf{r},t)$

$$\varphi(t) = \omega_0 t - k_0\, n(t)\, \ell$$

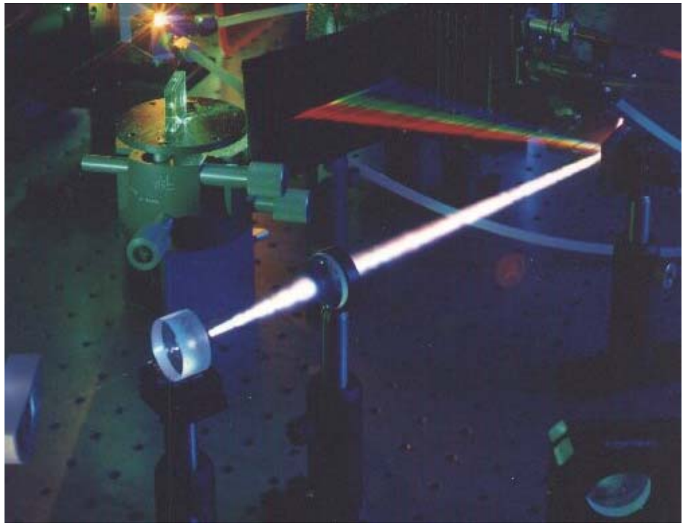
$$\omega(t) = \frac{d\varphi}{dt} = \omega_0 - k_0 n_2 \frac{dI(t)}{dt} \ell$$



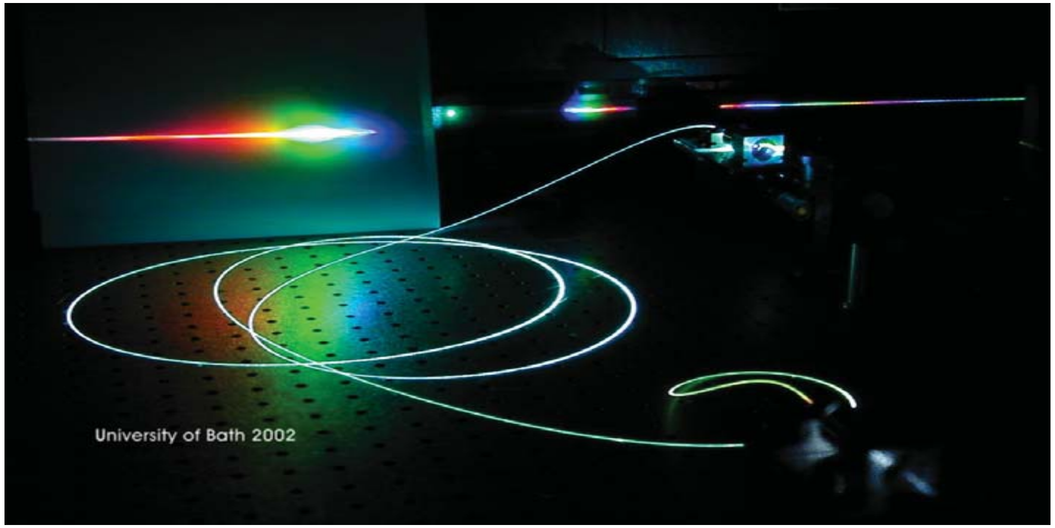


Spectral Broadening by SPM

In a bulk piece of glass:
non uniform SPM



In a photonic crystal fiber: uniform SPM



High-resolution Spectroscopy and Laser Cooling

Doppler-free Spectroscopy

- Saturation Spectroscopy:
  Two oppositely traveling laser beams at $\omega=\omega_0$ produce a more pronounced saturation of the Doppler-broadened absorption line (Lamb dip); width of the dip is equal to homogeneous line of the transition $\Rightarrow$ Doppler-free spectroscopy
- Two-photon spectroscopy
  Two oppositely traveling laser beams at $\omega=\omega_0/2$ produce, by two photon absorption a more pronounced two photon fluorescence; width of this enhancement is equal to homogeneous line of the transition $\Rightarrow$ Doppler-free spectroscopy

Laser Cooling and Trapping

- **Laser cooling:**
  A laser beams at $\omega > \omega_0$ interact with atoms with υ_z opposite to beam propagation $\Rightarrow$ cooling of atom due to recoil effect $\Rightarrow$ two oppositely propagating laser beams cool υ_z component of the atom

- **Atom trapping**
  Use of Magneto-Optical Trap (MOT)

A Bridge between Laser Science

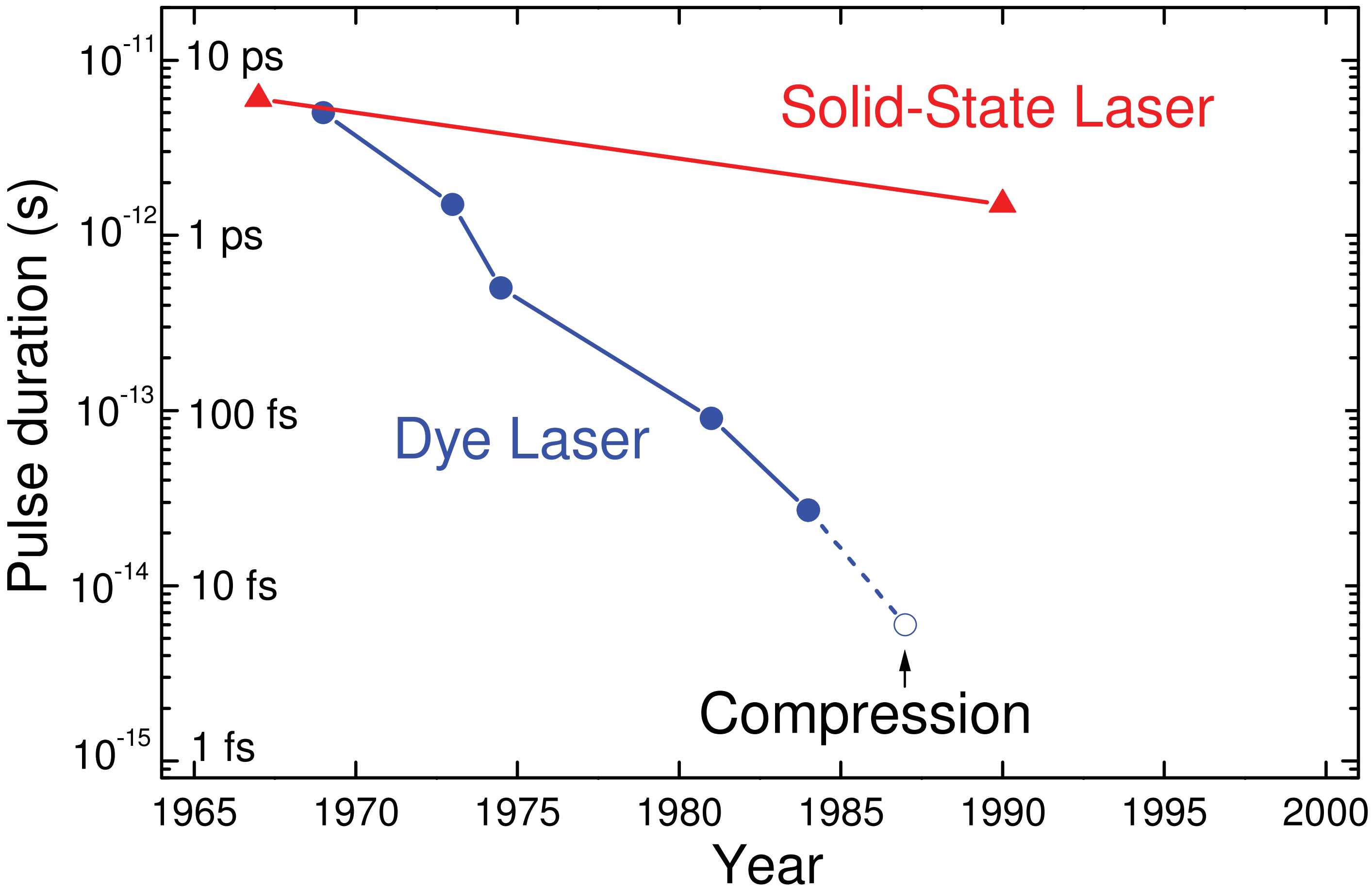
And Nonlinear Optics:

Ultrafast Laser Science

Historical Evolution of Pulse Duration (Phase 1)

Solid state (Ruby and Nd) and Dye Lasers

From picosecond to subpicosecond



Picosecond Laser Pulses

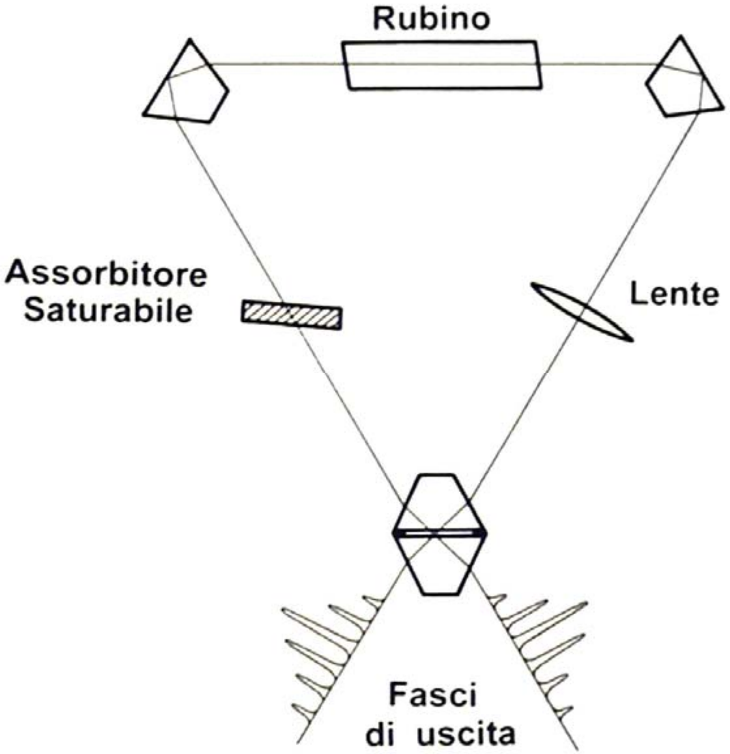
- ML solid stated lasers (Ruby and Nd:glass)
  A.J. De Maria
  R.R. Alfano and S.L. Shapiro
  W. Kaiser

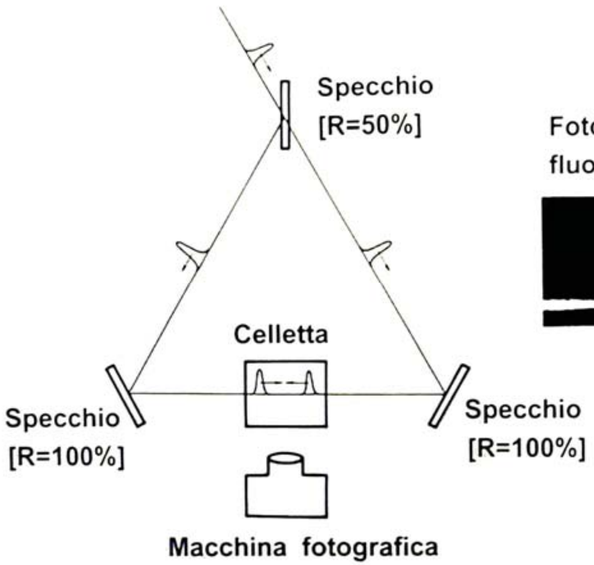
- ML dye lasers
  E.I. Ippen and C.V. Shank

Radiationless transitions and energy transfer

The Ring-type Ruby Laser

- Ring laser $\Rightarrow$ TEM$_{00}$ mode oscillation $\Rightarrow$ $\Delta\tau$ = 5 ps (1969)



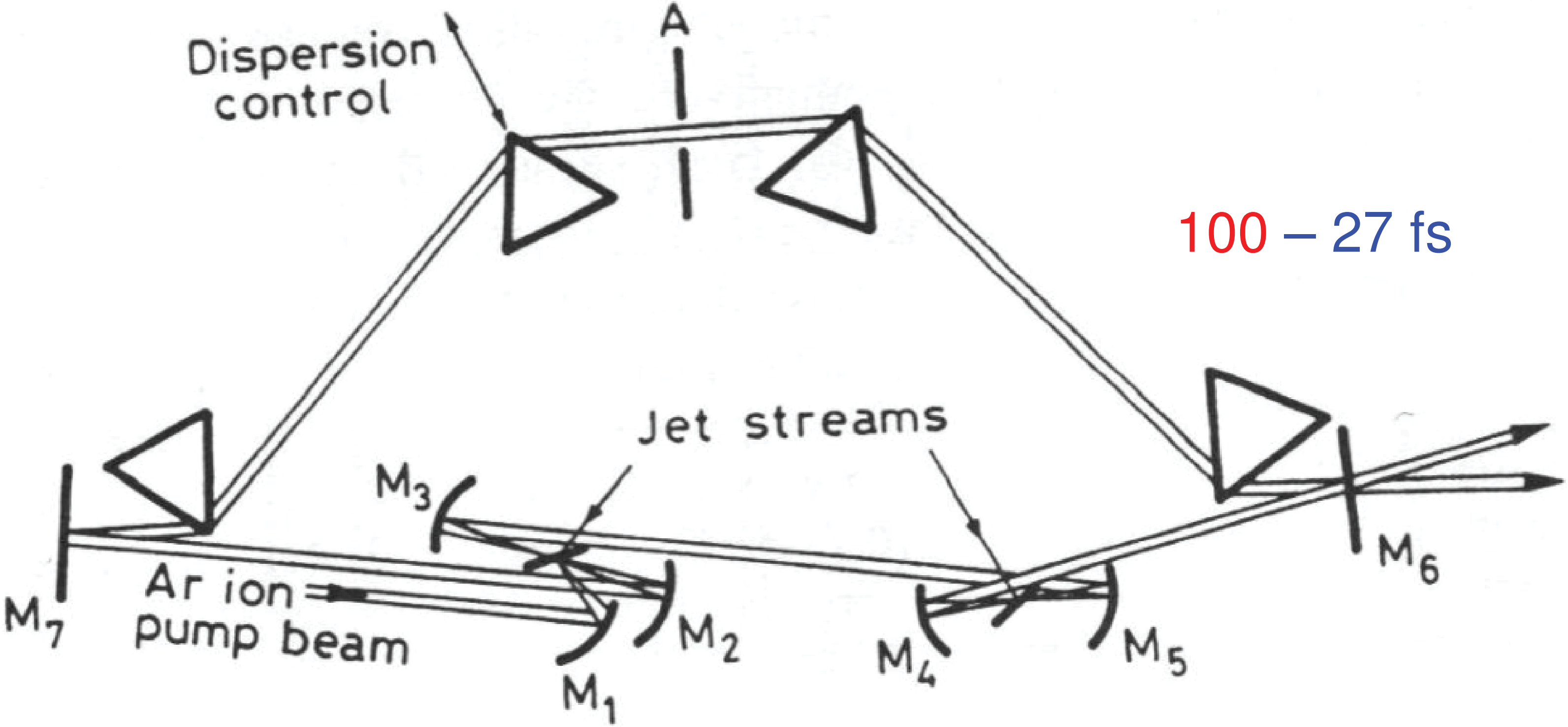


Fotografia della
fluorescenza a due fotoni

R. Cubeddu *et. al. IEEE J. Quant. Electr.* **QE-5**, 470 (1969)

Breaking the Picosecond Barrier

The colliding-pulse mode-locked (CPM) dye laser
[E.P. Ippen and C.V. Shank (1974),
C.V. Shank, F.L. Fork, B.I. Greene]

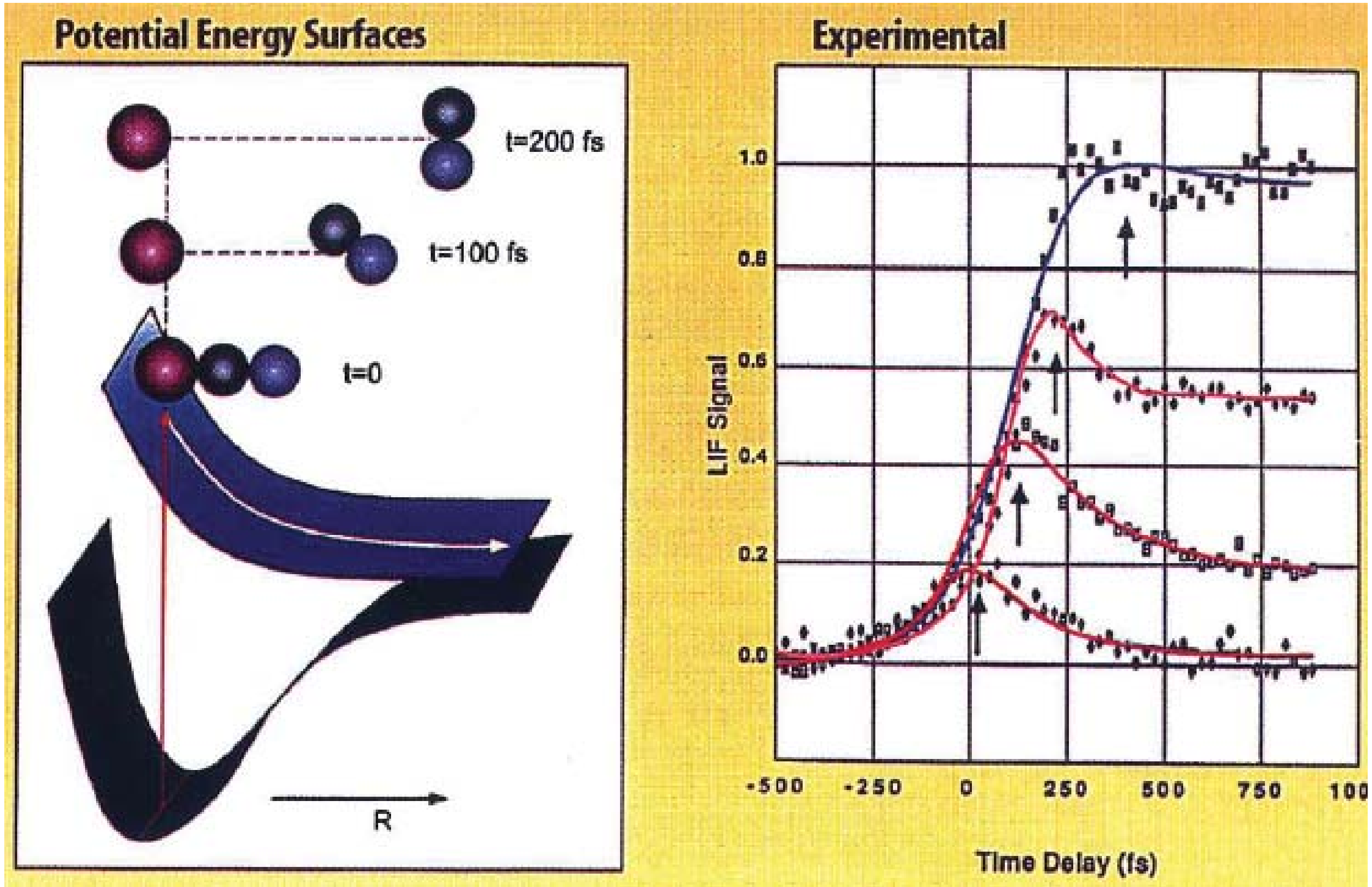


100 – 27 fs

Application: Femtochemistry

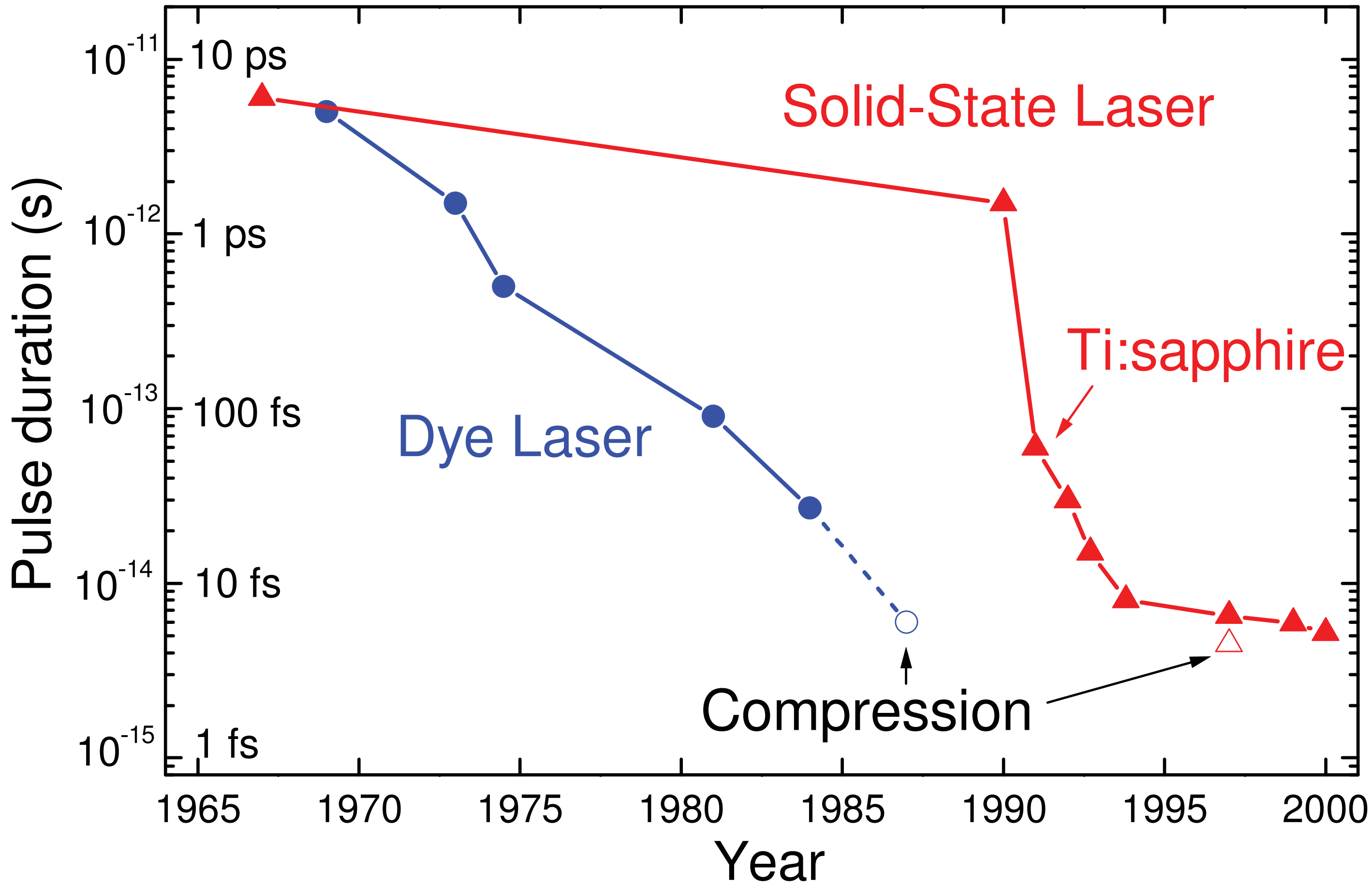
Ahmed H. Zewail, Nobel Prize in Chemistry (1999)

ICN, paradigmatic molecule for dissociation reactions and photofragment spectroscopy



Historical Evolution of Pulse Duration (Phase 2)

From sub-picoseconds to femtoseconds
High peak-intensity lasers



Newcomers: Tunable Solid State Lasers

- Laser-pumped solid-state lasers (beginning of nineties)
  Alexandrite
  Cr:LISAF
  Cr:YAG
  Ti:Sapphire

Bye-bye to dyes

The Dye Laser

First exciting example of widely tunable laser

- First laser action independently achieved by:

P.P. Sorokin and J.R. Lankard,
Stimulated Emission observed from an Organic Dye, Chloro-Aluminum Phtalocyanine
IBM J. Res. Dev. **10**, 162 (1966)

F.P. Schäfer, W. Schmidt, J. Voltze
Organic Dye Laser Solution
Appl. Phys. Lett. **9**, 305 (1966)

Applications of Dye Lasers

- Laser spectroscopy

  It immediately became the work horse for spectroscopists

- Ultrafast Sciences

  Mode-locked dye lasers (<100 fs in 1980, beginning of femtosecond laser sciences)

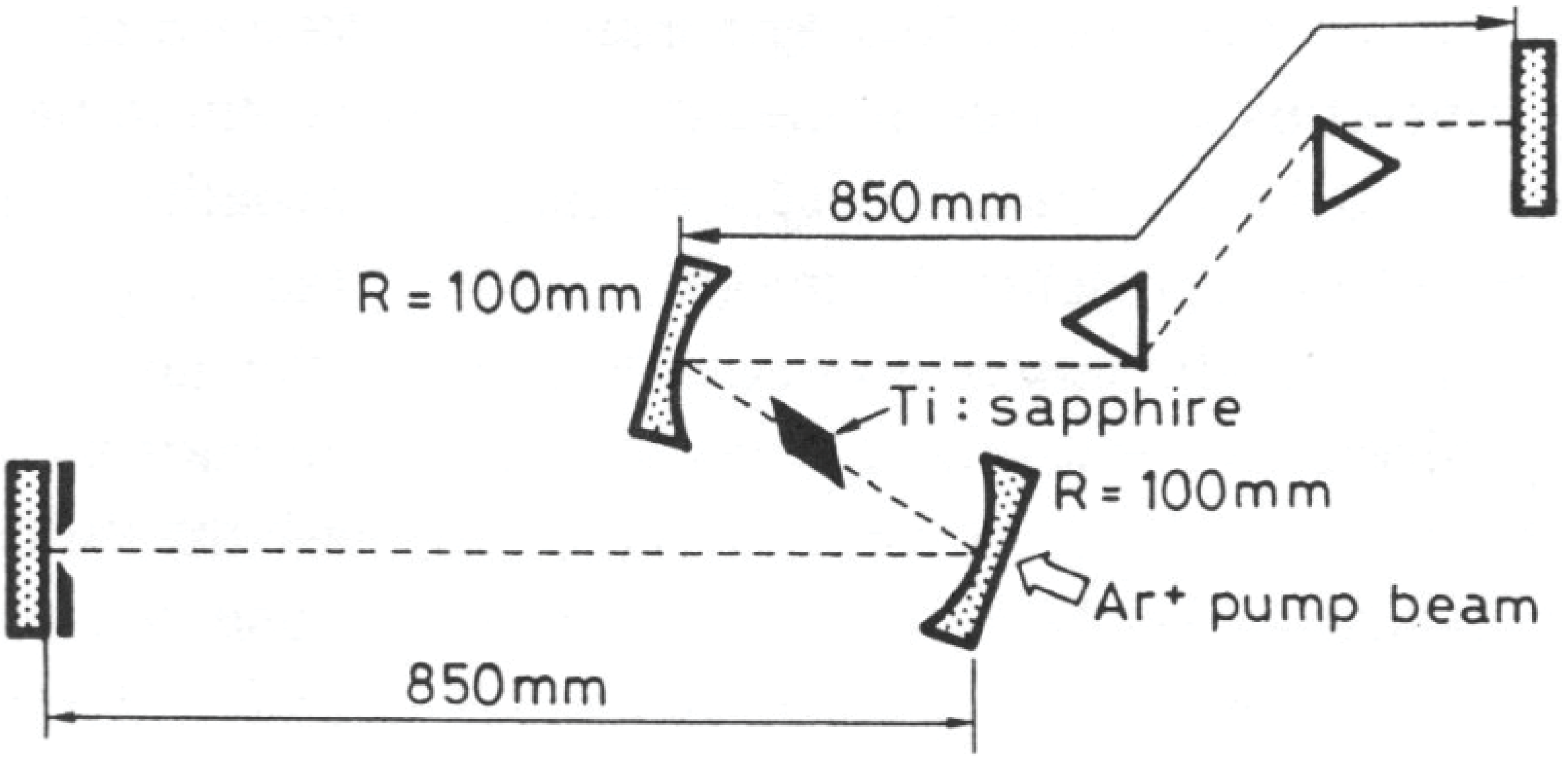
Dye Lasers were just Great

- You could eat it

  The edible laser (Arthur L. Schawlow)
- You could drink it

  The drinkable laser (Eastman Kodak Labs Rochester)
- You could make life quite colorful

Kerr-Lens ML Ti:sapphire

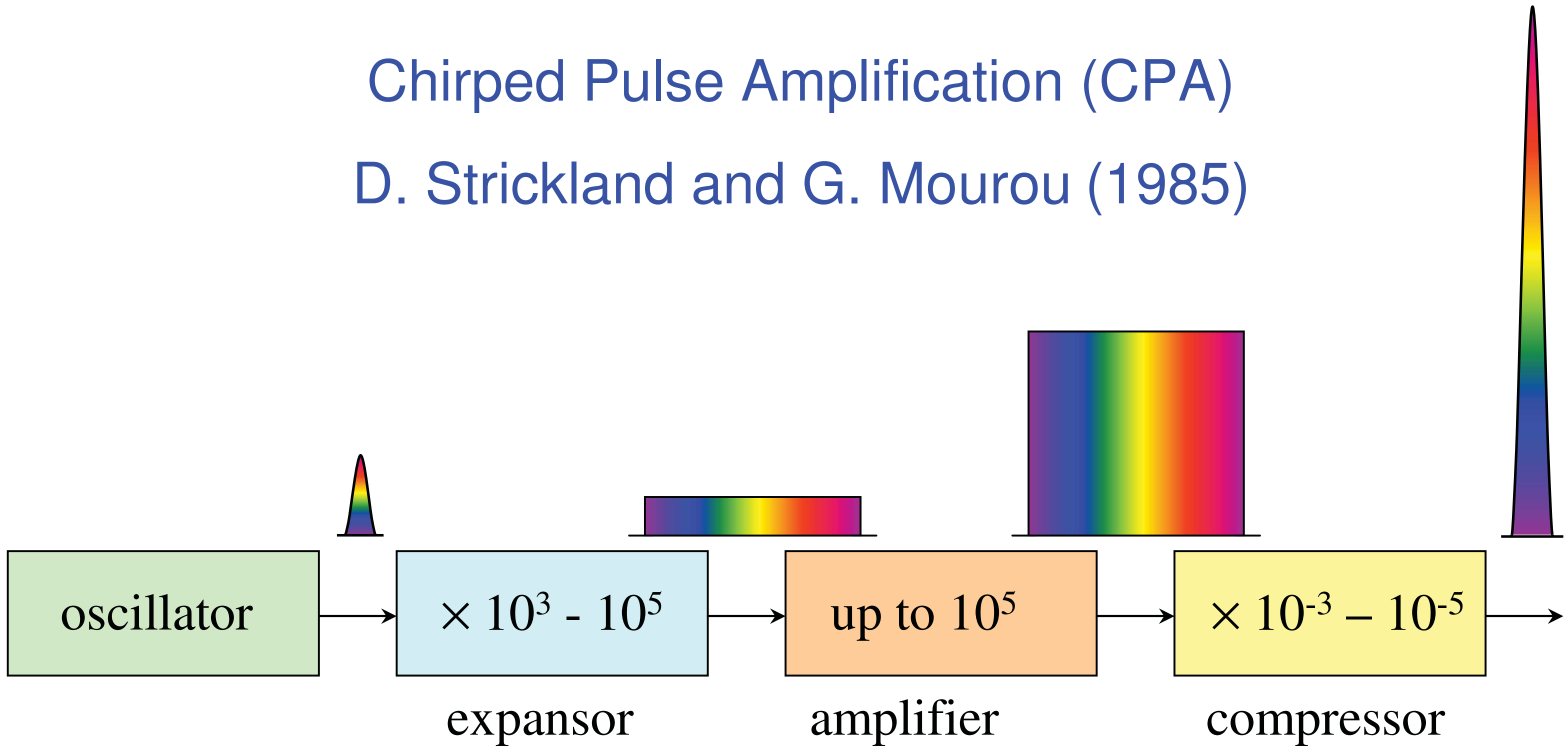


D.E. Spence, P.K. Kean, and W. Sibbet *Opt. Lett.* **16**, 42 (1991)
M. Piché, *Opt. Commun.* **86**, 156 (1991)
Patent for the Aperture (Coherent)

High Peak Intensities Lasers

Chirped Pulse Amplification (CPA)

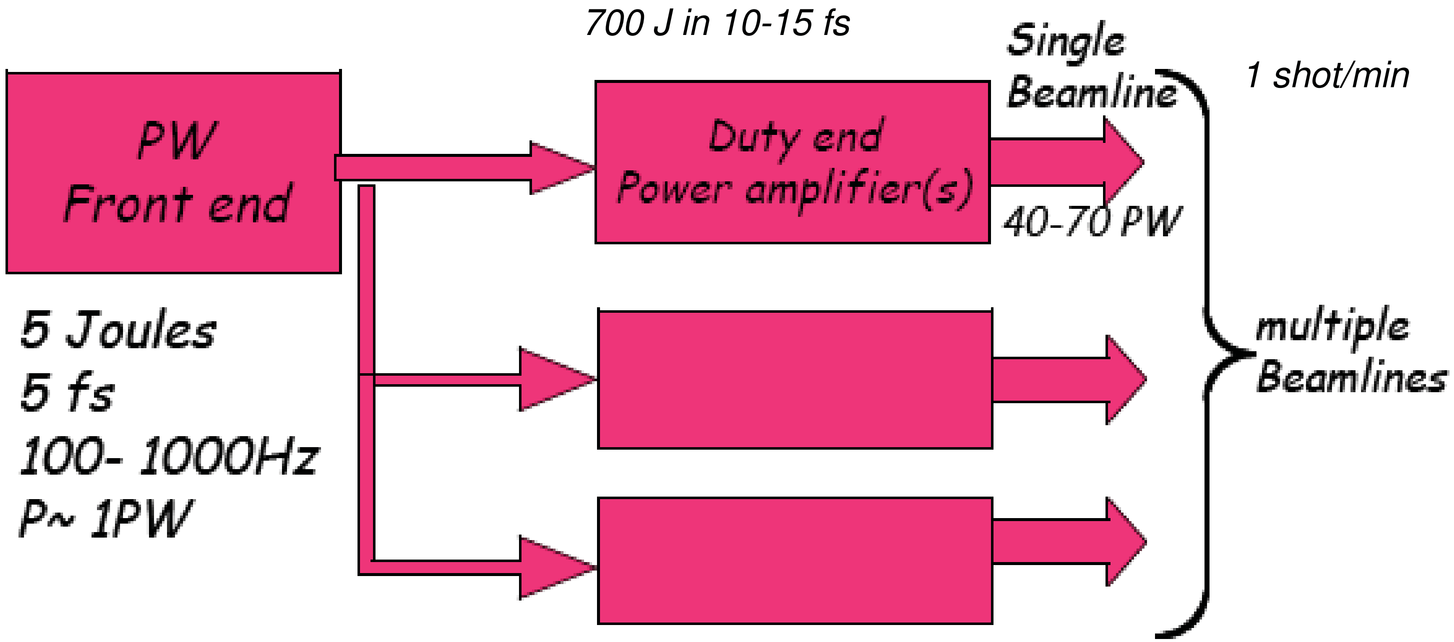
D. Strickland and G. Mourou (1985)



- $Ti:Al_2O_3$: 1-10 mJ; f = 1-10 kHz
- TTT [Terawatt Table Top] Lasers : 100 TW (5 J, 50 fs)
- Petawatt-class Lasers (1,5 PW, i.e. 580 J and 460 fs)

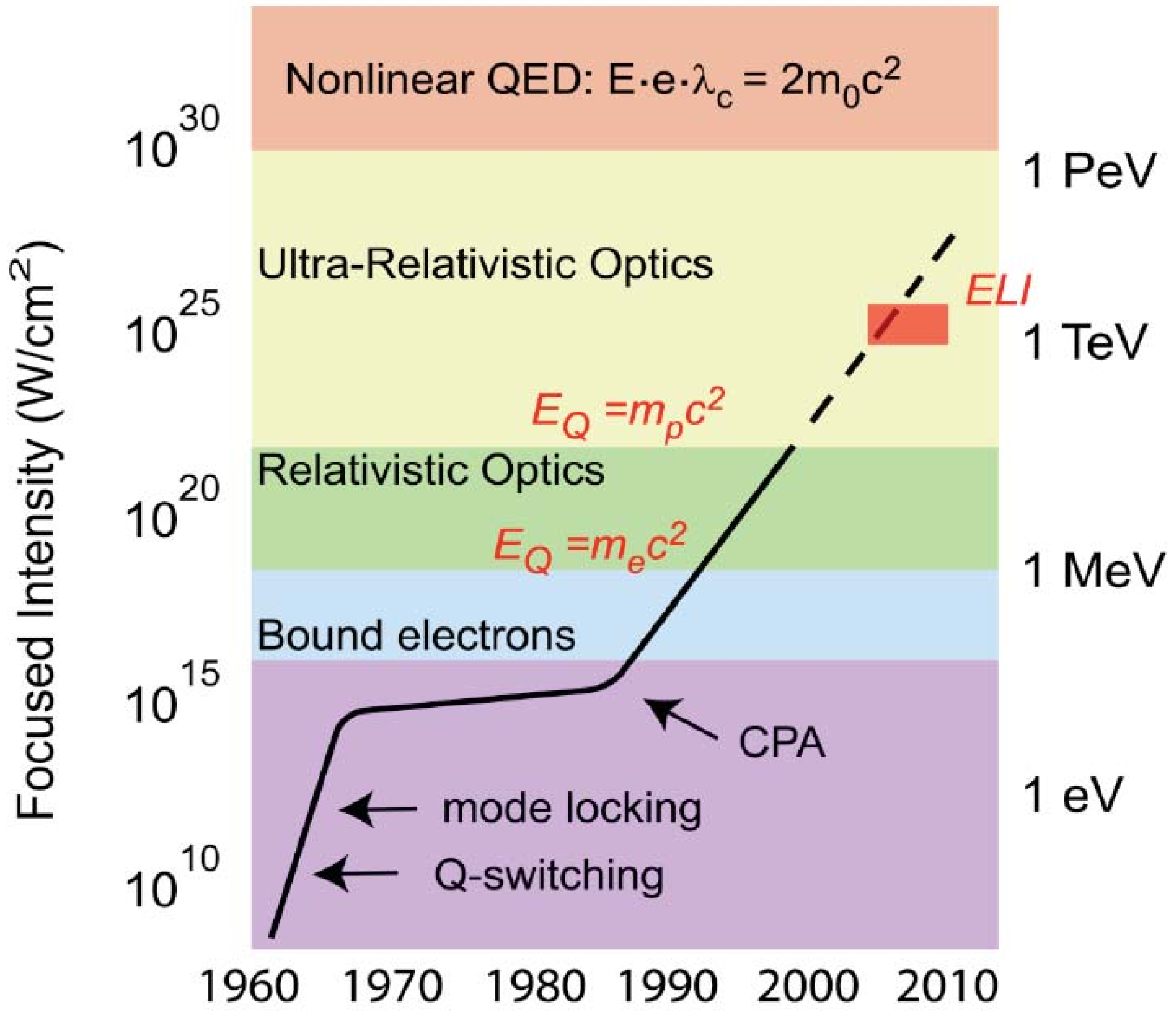
The ELI Project

Extremely Large Infrastructure (ELI)
G. Mourou



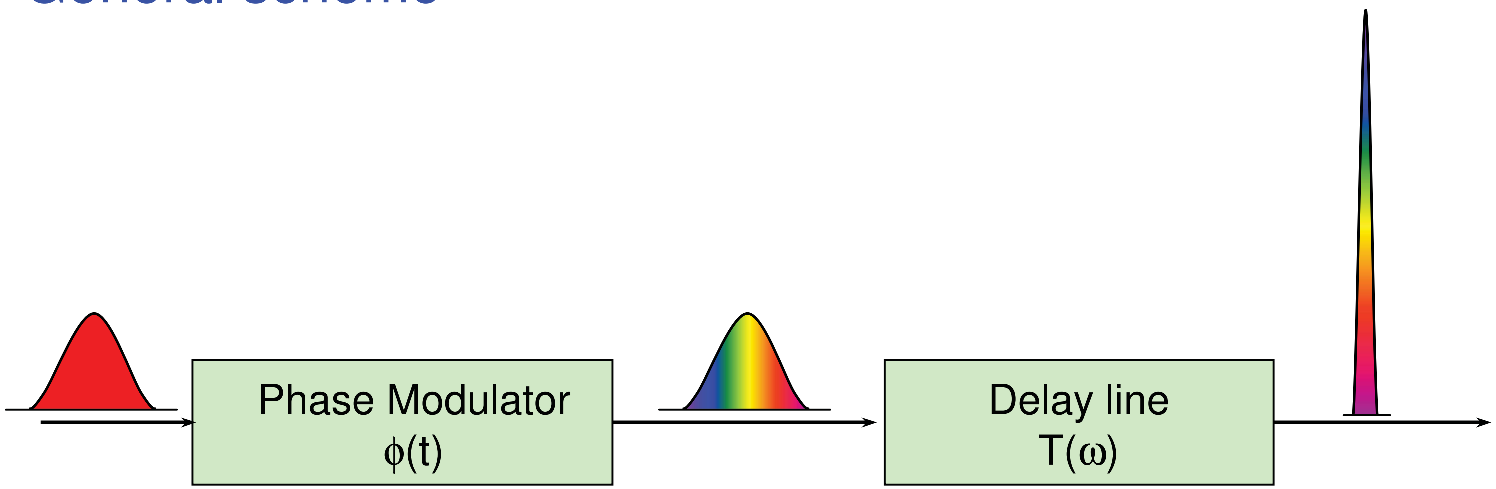
100 PW on target ~ 10^{25} W/cm^2

Historical Evolution of Peak Intensity



Compression of Light Pulses

- General scheme



Phase Modulator: generation of extra-frequency band

Delay line: re-phasing of the new frequency components

Hystorical Remarks on Pulse Compression

- Proposal by e-o frequency modulators

  F. Gires and P. Tournois, Compt. Rend. **258**, 6112 (1964)

  J. A. Giordmaine, M.A. Duguay, and T.K. Gustafson

  IEEE J. Quant. Electr. **QE-4**, 252 (1968)
- Proposal by self-phase-modulation (SPM)

  R.A. Fisher, P.L. Kelley and T.K. Gustafson

  Appl. Phys. Lett. **14**, 140 (1969)
- SPM in optical fibers

  D. Grisckowsky and A.C. Balant

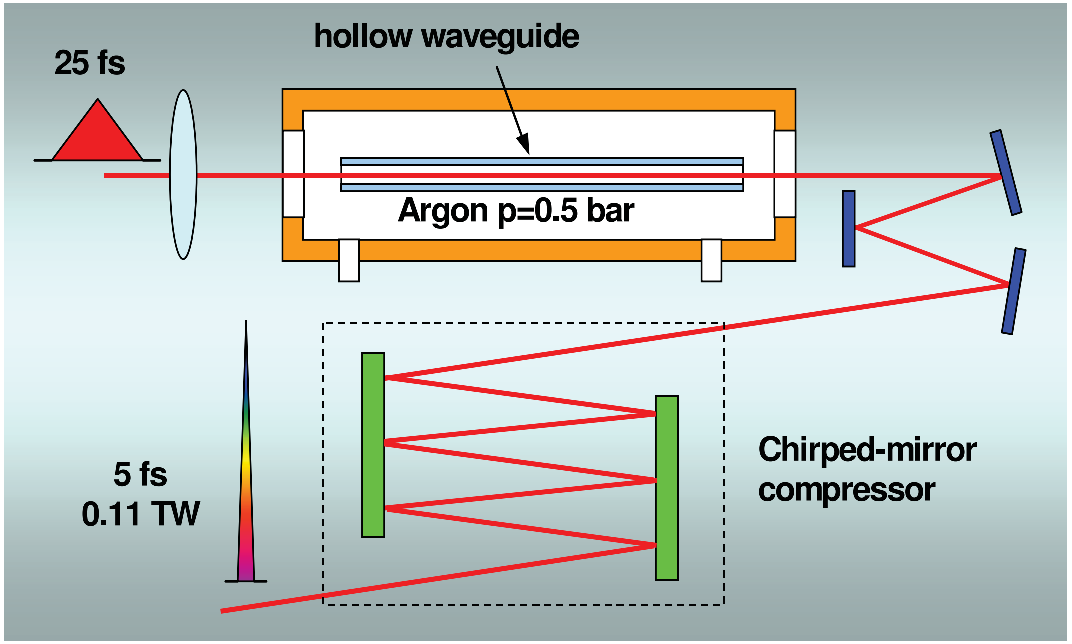
  Appl. Phys. Lett. **41**, 1 (1982)
- 6 fs from dye lasers

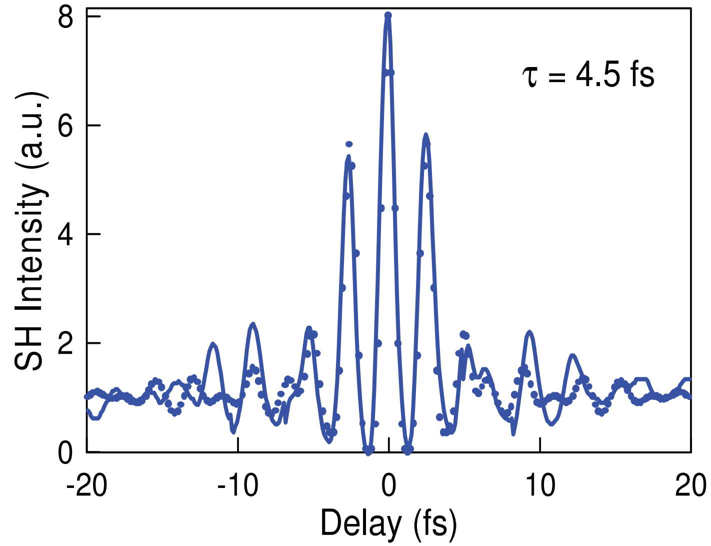
  R.L. Fork *et. al.*, Opt. Lett. **12**, 483 (1987)

All f.o. experiments at very low input energy (< 10 nJ)

High-Energy Pulse Compression

Hollow-fiber Compressor (1-10 mJ)



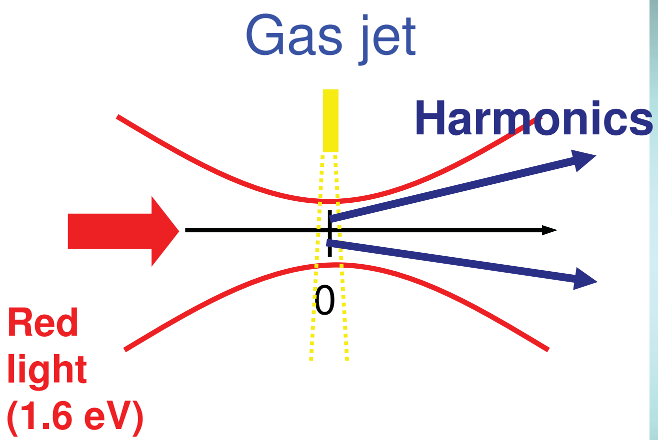


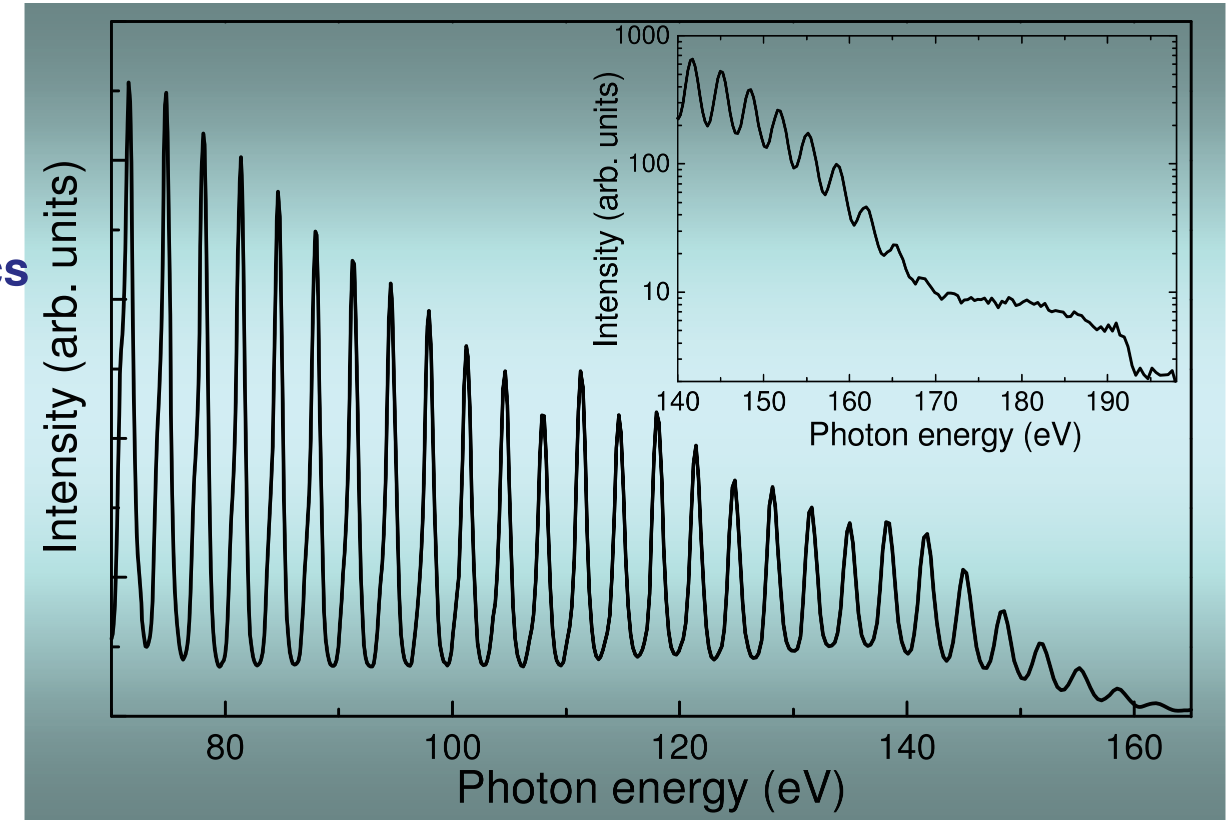
Near-single-cycle laser pulses

M. Nisoli, S. DeSilvestri, and O. Svelto, Appl. Phys. Lett. **68**, 2793 (1996)
M. Nisoli *et al.*, Opt. Lett. **22**, 522 (1997)

High Order Harmonic Generation
HHG

Very-short pulses in the X-UV range



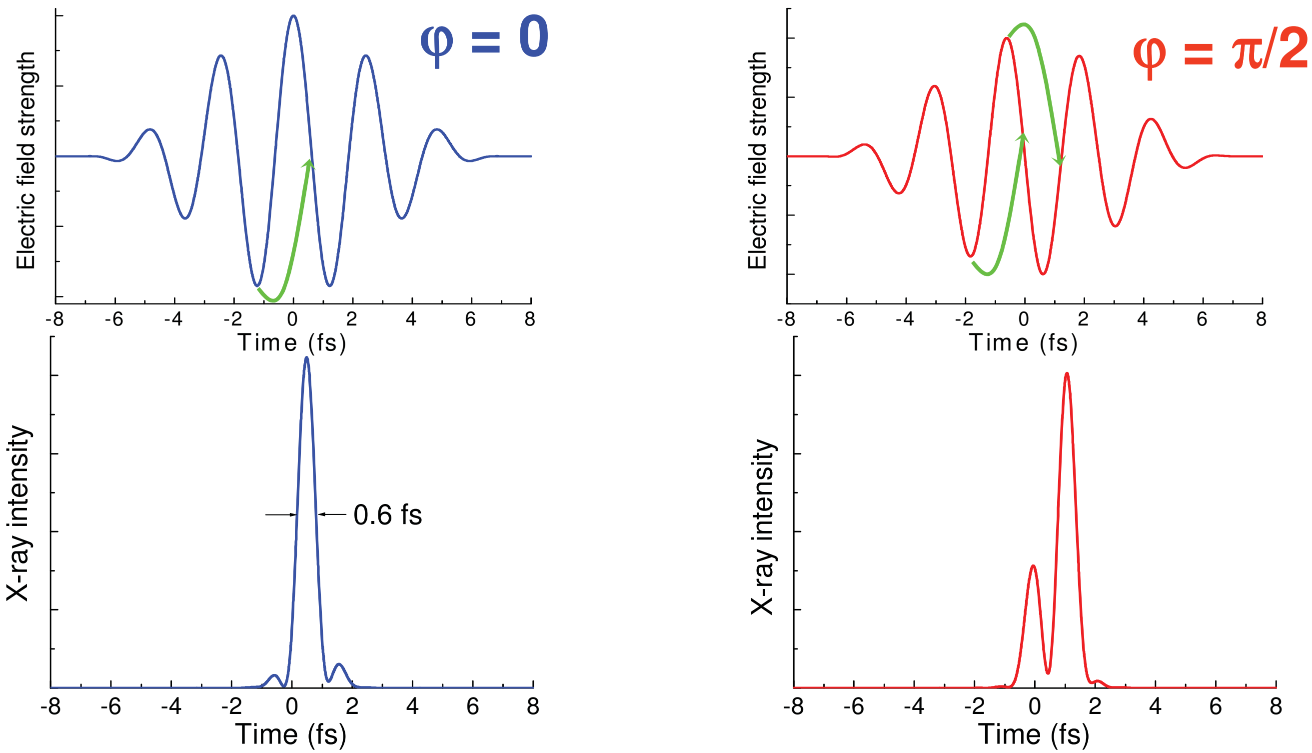


Anne L'Huillier pioneering work [PRL **70**, 774 (1993)
P.B. Corkum, PRL **71**, 1994 (1993)

➔ Odd harmonics of the red light are generated up to the soft X ray region

HHG by near-single-cycle laser pulses

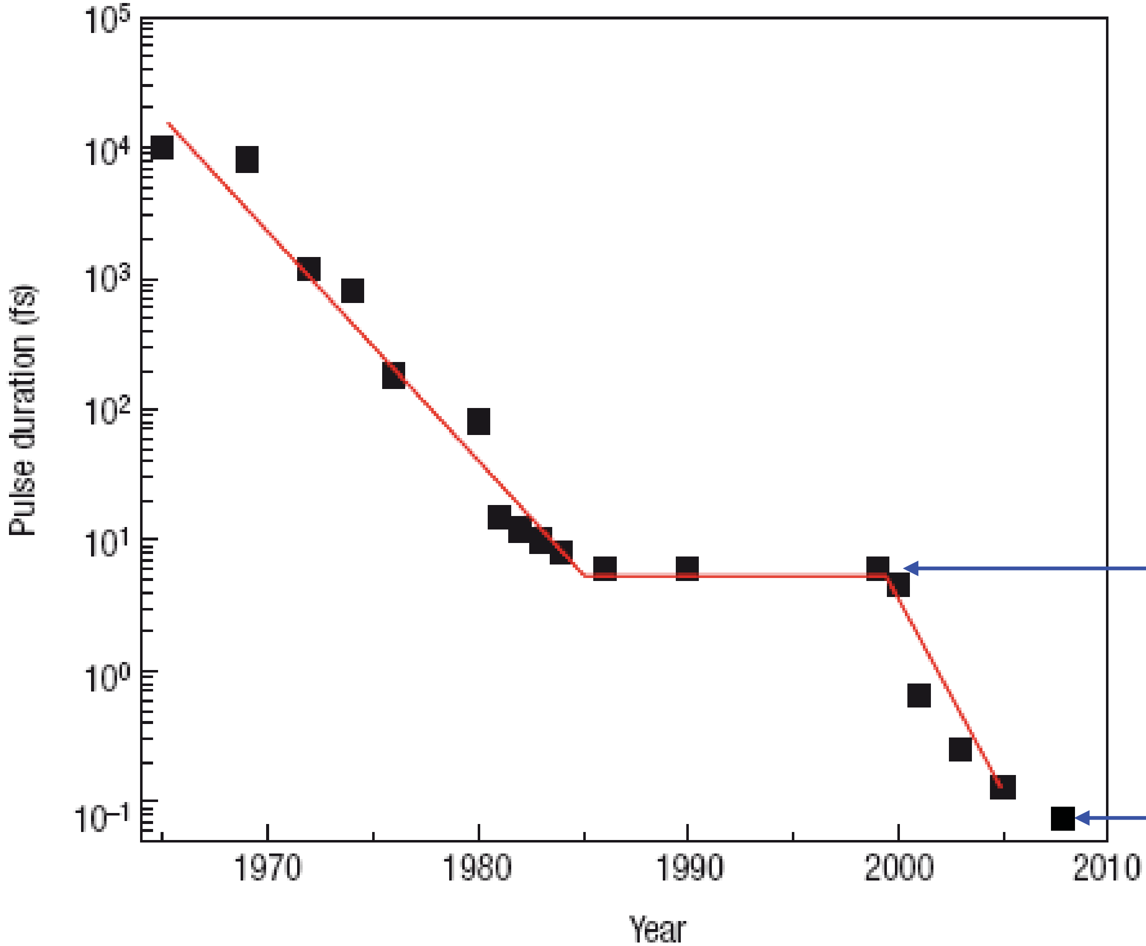
- Near-single cycle laser pulses of high energy [$E(t)=A(t)\cos(\omega t+\varphi)$]



Generation of isolated attosecond laser pulses

Historical Evolution of Pulse Duration (Phase 3)

From Femtoseconds to Attoseconds



4 fs

80 as: E. Goulielmakis *et. al.*, Science **320**, 1614 (2008)

The Future of Ultrafast Sciences

- Extremely-high peak intensity ($10^{22} \div 10^{25}$ W/cm^2)

  High-field Physics

- Extremely-short time duration (100 ÷ 10 as)

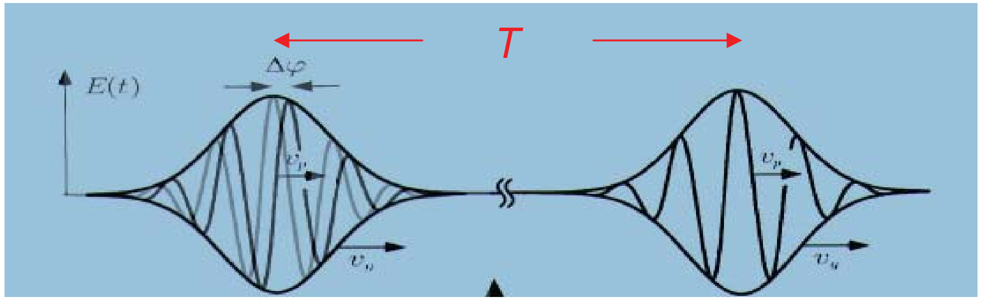
  Attosecond Science

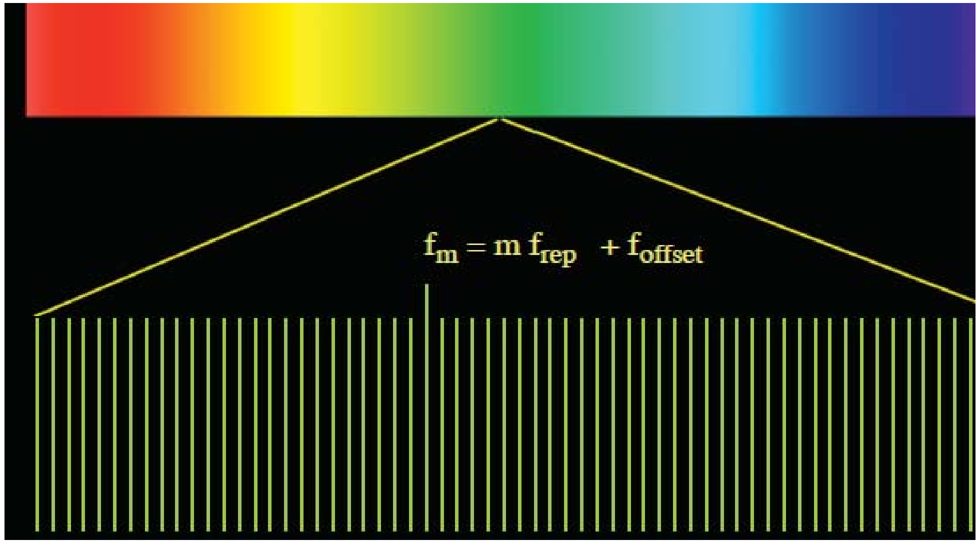
A Bridge between Laser Spectroscopy and Ultrafast Laser Science:

The Frequency Comb

The Frequency Comb

Theodor W. Hänsh e John L. Hall, Nobel Prize for Physics (2005)





$\Delta\varphi$ = phase offset between carrier wave and wave envelope

$f_m = mf_{rep} + f_{offset}$

$f_{rep} = 1/T$

$f_{offset} = (\Delta\varphi/2\pi)\, f_{rep}$

Therefore if

$\Delta\varphi = 0 \Rightarrow f_{offset} = 0 \Rightarrow$

$f_m = mf_{rep}$

The idea has revolutioned the art of frequency measurements ($10^{-14} \div 10^{-18}$)

Hystorical Remarks on Nobel Prizes 1

- 1964, Physics

  C. H. Townes (1/2) and N.G. Basov and A. M. Prokhorov (1/2)
  for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle
- 1971, Physics

  Denis Gabor
  for his invention and development of the holographic method
- 1981, Physics

  Nicolas Bloembergen an Arthur L. Schawlow
  for their contributions to the development of laser spectroscopy
- 1997, Physics

  Steven Chu, Claude Cohen-Tannoudji and William D. Philips
  for development of methods to cool and trap atomswith laser light

Hystorical Remarks on Nobel Prizes 2

- 1999, Chemistry
  Ahmed H. Zewail
  for his studies of the transition states pf chemical reactions using femtosecond spectroscopy
- 2000, Physics
  Zhores I. Alferov and Herbert Kroemer
  for developing semiconductot hetrostructures used in high-speed-electronics and -optoelectronics
- 2001, Physics
  Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman
  for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fuindamental studies of the properties of the condensates

Hystorical Remarks on Nobel Prizes 3

- 2005, Physics
  Roy Glauber (1/2),
  for his contribution to the quantum theory of optical coherence
  John L. Hall and Theodore W. Hänsch (1/2)
  for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique
- 2009, Physics
  Charles K. Kao (1/2)
  for ground-breaking achievements concerning the transmission of light in fibers for optical communications
- 2012, Physics
  Serge Haroche and David Wineland
  for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems

Early developments in laser applications

(1960-1970)

A Very Frustrating Period (1960-1970)

Application-wise many initial attempts failed

- **Medicine**: retina photocoaugulation, port-wine stains, melanoma (pulsed ruby)
- **Optical Communications** (Ruby or He-Ne, hollow-fibers or periodic gas lenses; optical fibers 1000 dB/km)
- **Material working** (50 W/m, slow-axial-flow CO_2 laser)

A bright solution looking for a problem

A 2 kW CO_2 Laser

A Magic Turning Point

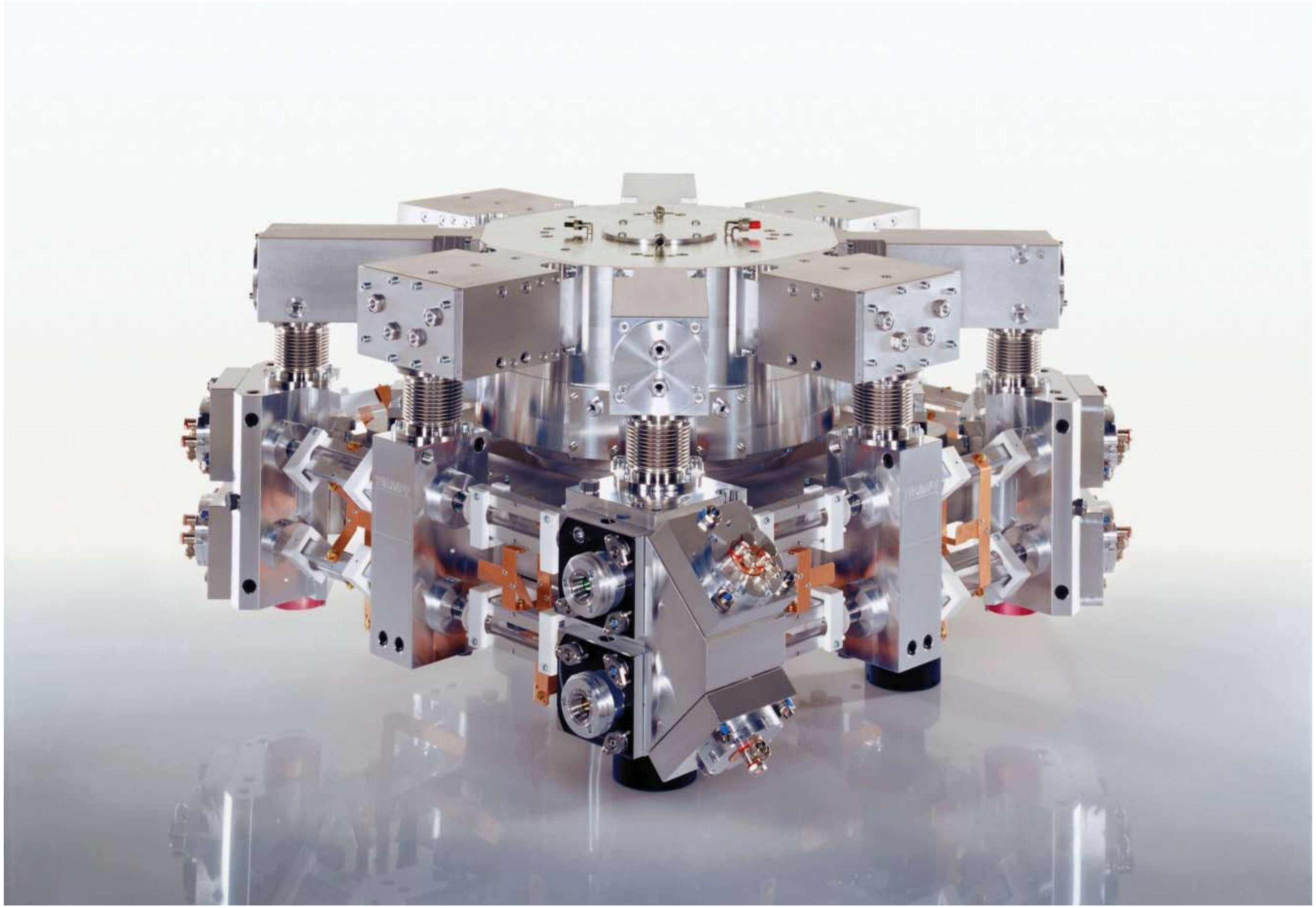
- Year seventies

  Medicine: retina photocoaugulation (Ar^+ ion), port-wine stains (pulsed dye lasers), melanoma (forget about it)

  Optical Communications: DH semiconductor laser (Alferov, 1970), Optical Fibers (Kao, 1966, Corning 17 dB/km, 1970)

  Material working: fast transverse flow (beginning of seventies) and fast longitudinal flow (late seventies) CO_2 laser

Fast Longitudinal Flow CO_2 Laser



Conclusions 1

- **Laser,** Early Days:

  A Bright Solution Looking for a Problem

- **Laser,** ~ Fifty Years Afterwards:

  The Bright Solution for many Problems in Science, Technology and Applications

Bright solution in science and technology: there is no field, in science and technology, which has not been changed, often in a dramatic way, by the invention of the laser. So far, 21 scientists have been awarded the Nobel Prize for researches on lasers or with lasers.

Conclusions 2

The Bright Solution for many Problems in Science, Technology and Applications

Bright solution for applications: "It has changed the way we live" (from letter of Barak Obama for the 50° anniversary of laser) [internet, DVD, laser printers, biomedical applications, industrial applications, optical measurements]

It is one of the most important inventions of last century.

It is going to play a even more important role in this century

The Century of the Photon
(2015 The Year of Light)