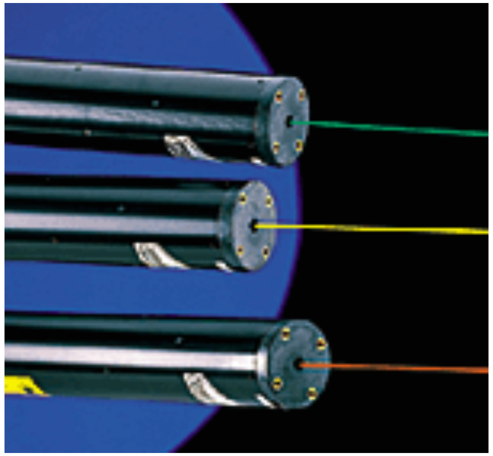


Quantum Electronics

Laser Physics

(AY 2023-2024)

Timetable

Tuesday: Live/In-Person 15:00-17:00 hrs X130

Friday: Live/By-Zoom 09:00-10:00 hrs (XG16)

LASER - Light Amplification via the Stimulated Emission of Radiation - *it's a Light Amplifier…*

Einstein worked out the basic mathematical and theoretical principles in the 1920s !!

The laser was invented 40 years later in 1960 in the Bell Laboratories in the USA.

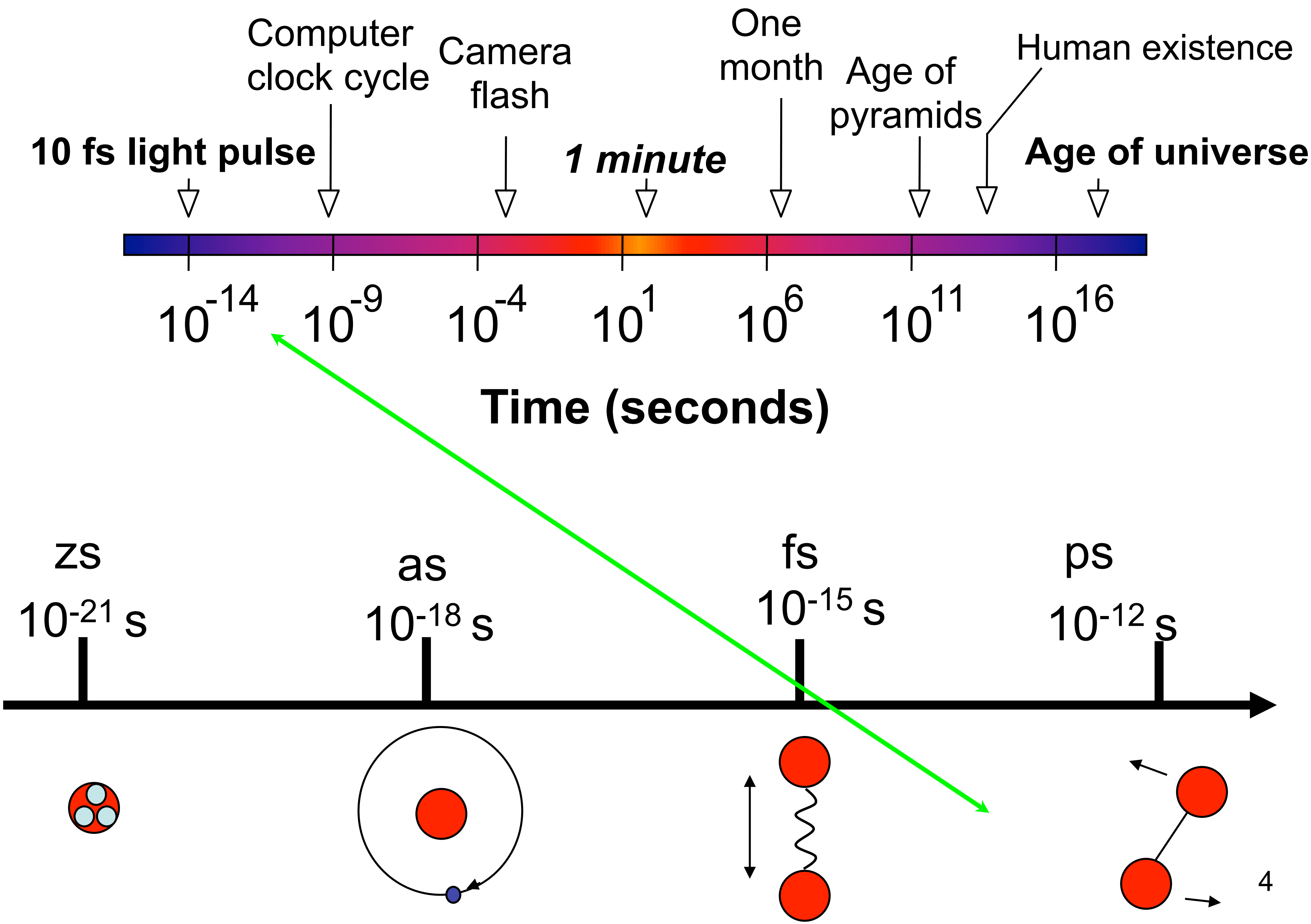
Lasers come in all sizes and shape and materials (gas, liquid, solid and plasma….

Scales in Physics

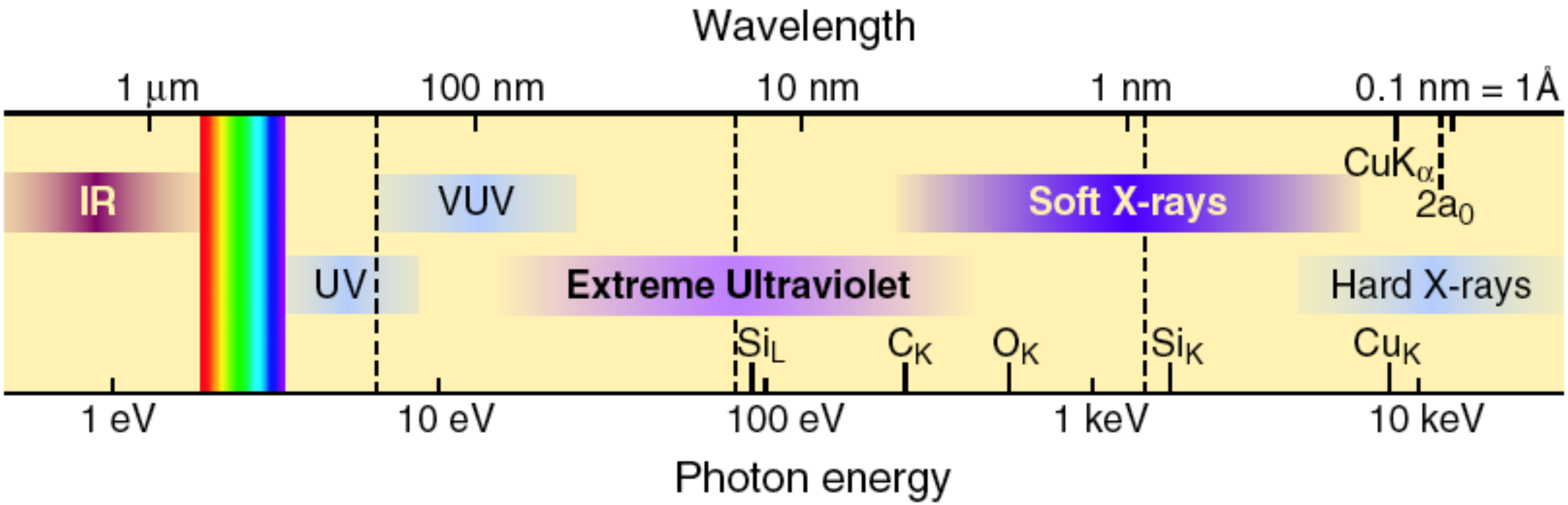
Small	Big
Milli (m) (1/1,000) 10^{-3}	Kilo (k) (1,000) 10^{+3}
Micro (μ) 10^{-6}	Mega (M) 10^{+6}
Nano (n) 10^{-9}	Giga (G) 10^{+9}
Pico (p) 10^{-12}	Tera (T) 10^{+12}
Femto (f) 10^{-15}	Peta (P) 10^{+15}
Atto (a) 10^{-18}	Exa (E) 10^{+18}
Zepto (z) 10^{-21}	Zetta (Z) 10^{+21}

Attosecond = 0.000000000000000001 seconds

TIMESCALES - HOW FAST IS FAST ?

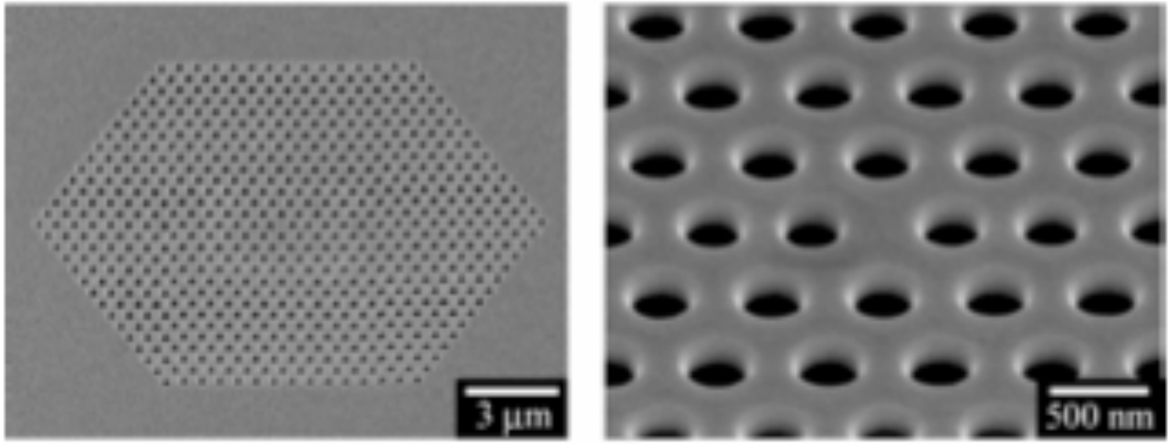


Electromagnetic Spectrum



Courtesy David Attwood Berkeley

Small - Nanolasers



(a)

Fig. 1. Scanning electron micrograph of fabricated
device. (b) Magnified view of the H0 nanolaser. Cen
laterally shifted.

- Nozaki et al., Optics Express, 11 June 2007 issue, full text available at http://www.opticsexpress.org/abstract.cfm?id=138211;

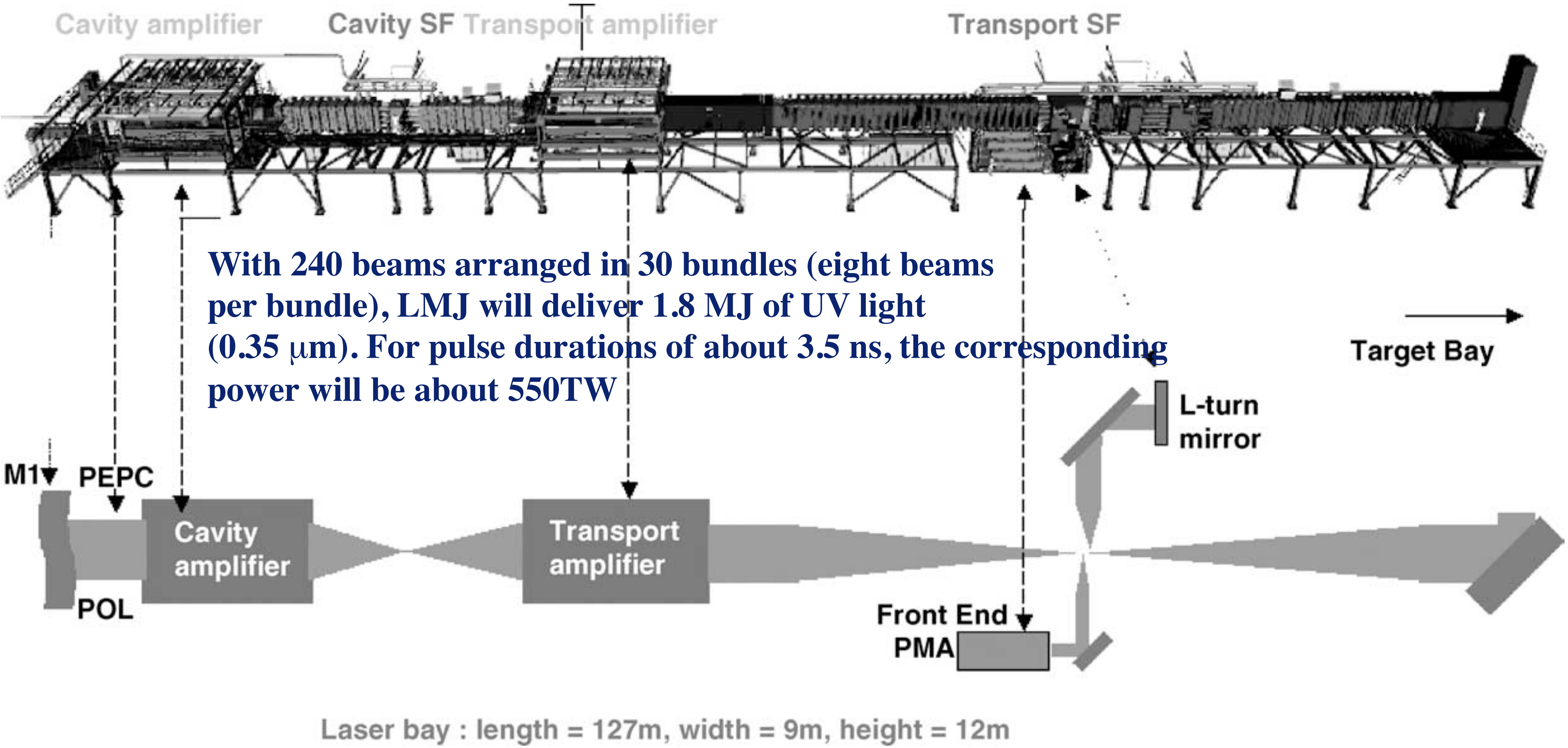
Room temperature continuous wave operation and controlled spontaneous emission in ultrasmall photonic crystal nanolaser

Kengo Nozaki, Shota Kita and Toshihiko Baba

Yokohama National University, Department of Electrical and Computer Engineering
79-5 Tokiwadai, Hodogayaku, Yokohama 240-8501, Japan
Email: baba@ynu.ac.jp

Abstract: Photonic crystal slab enables us to form an ultrasmall laser cavity with a modal volume close to the diffraction limit of light. However, the thermal resistance of such nanolasers, as high as 10^6 K/W, has prevented continuous-wave operation at room temperature. The present paper reports on the first successful continuous-wave operation at room temperature for the smallest nanolaser reported to date, achieved through fabrication of a laser with a low threshold of 1.2 µW. Near-thresholdless lasing and spontaneous emission enhancement due to the Purcell effect are also demonstrated in a moderately low Q nanolaser, both of which are well explained by a detailed rate equation analysis.

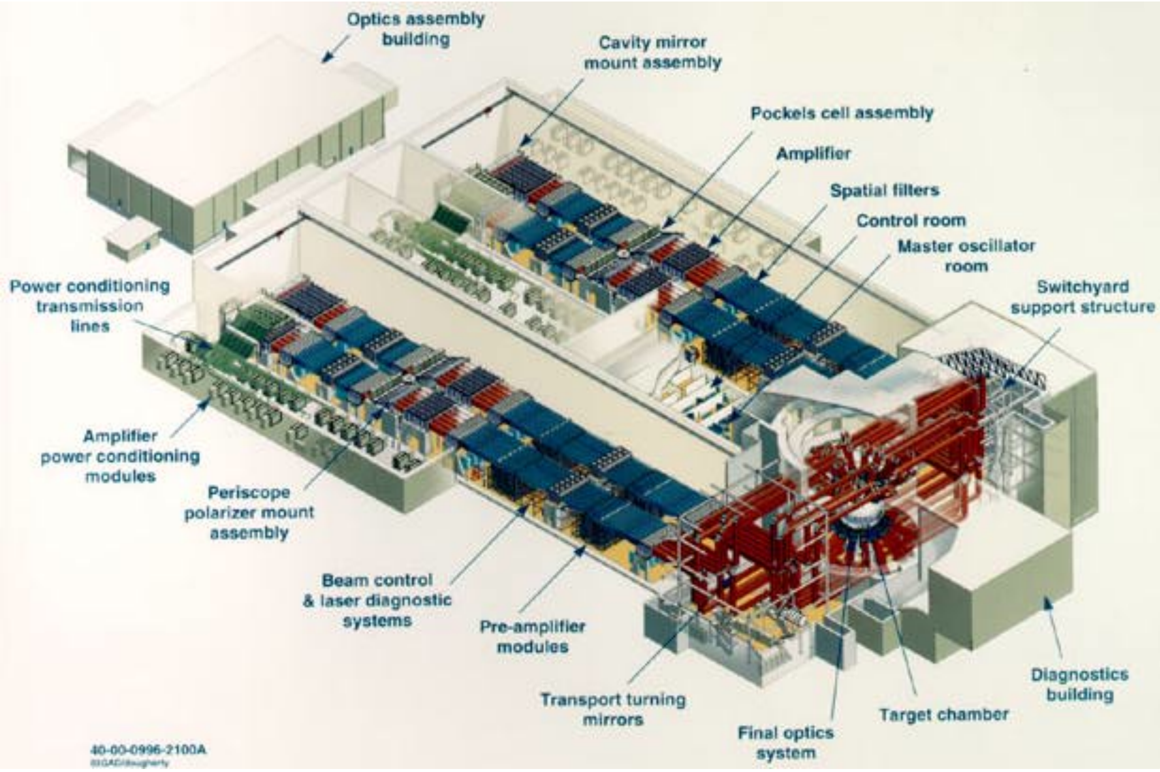
Big - The Mégajoule Laser

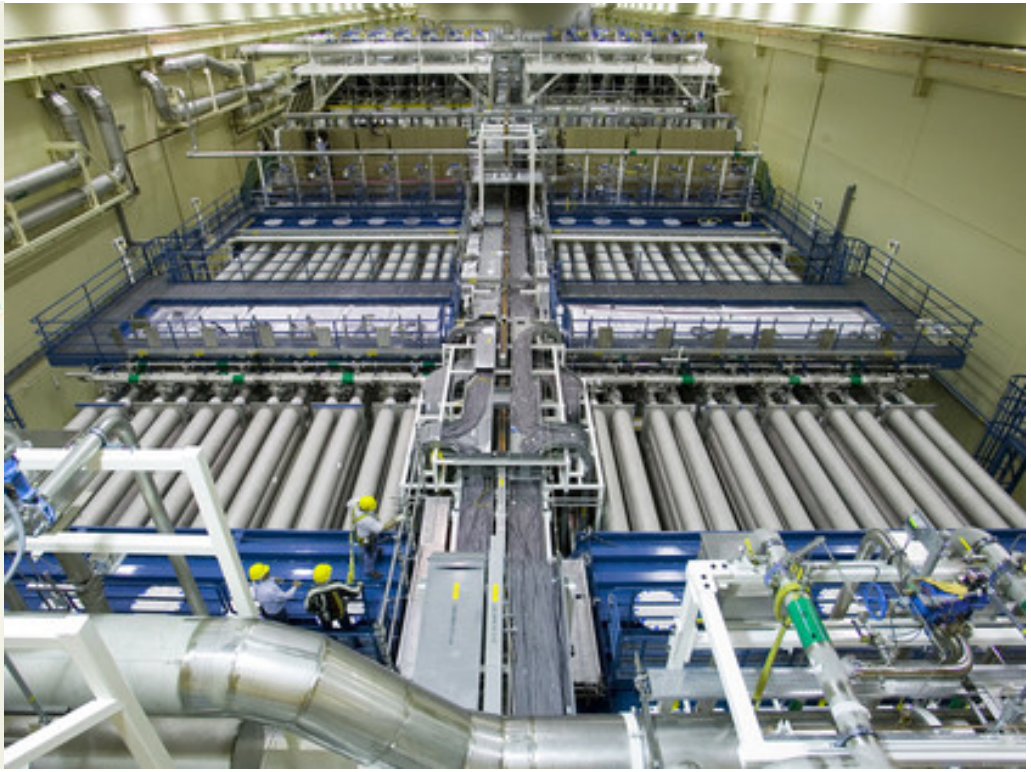


With 240 beams arranged in 30 bundles (eight beams per bundle), LMJ will deliver 1.8 MJ of UV light (0.35 μm). For pulse durations of about 3.5 ns, the corresponding power will be about 550TW

Fusion Engineering and Design 74 (2005) 147–154

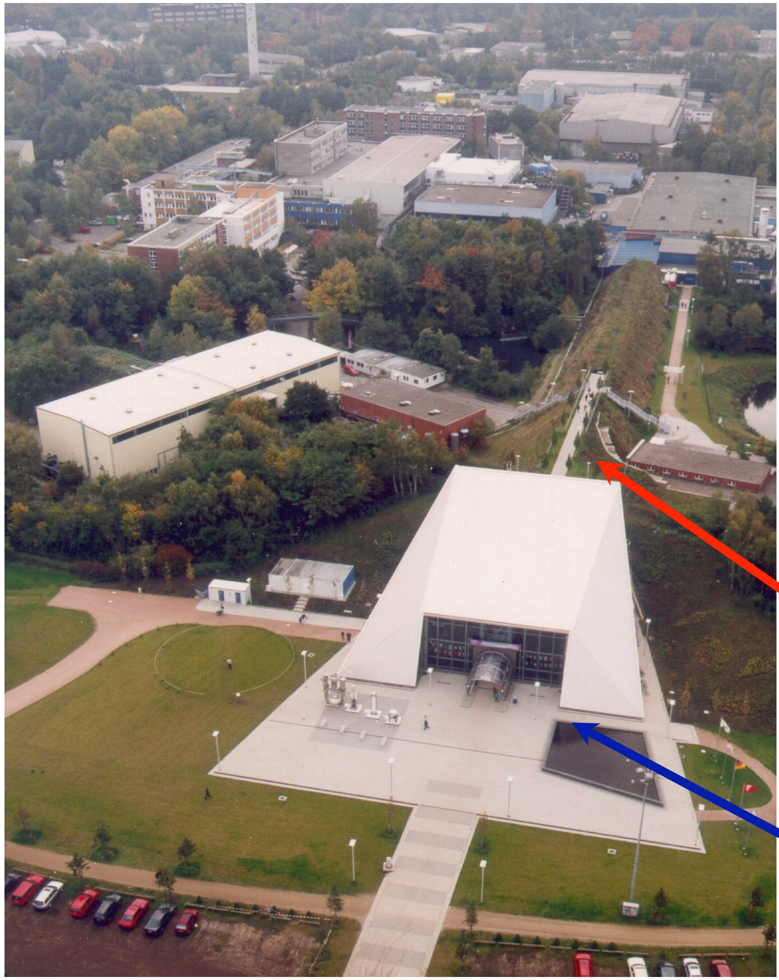
Very Big - The National Ignition Facility
NIF Lawrence Livermore National Lab, California, USA

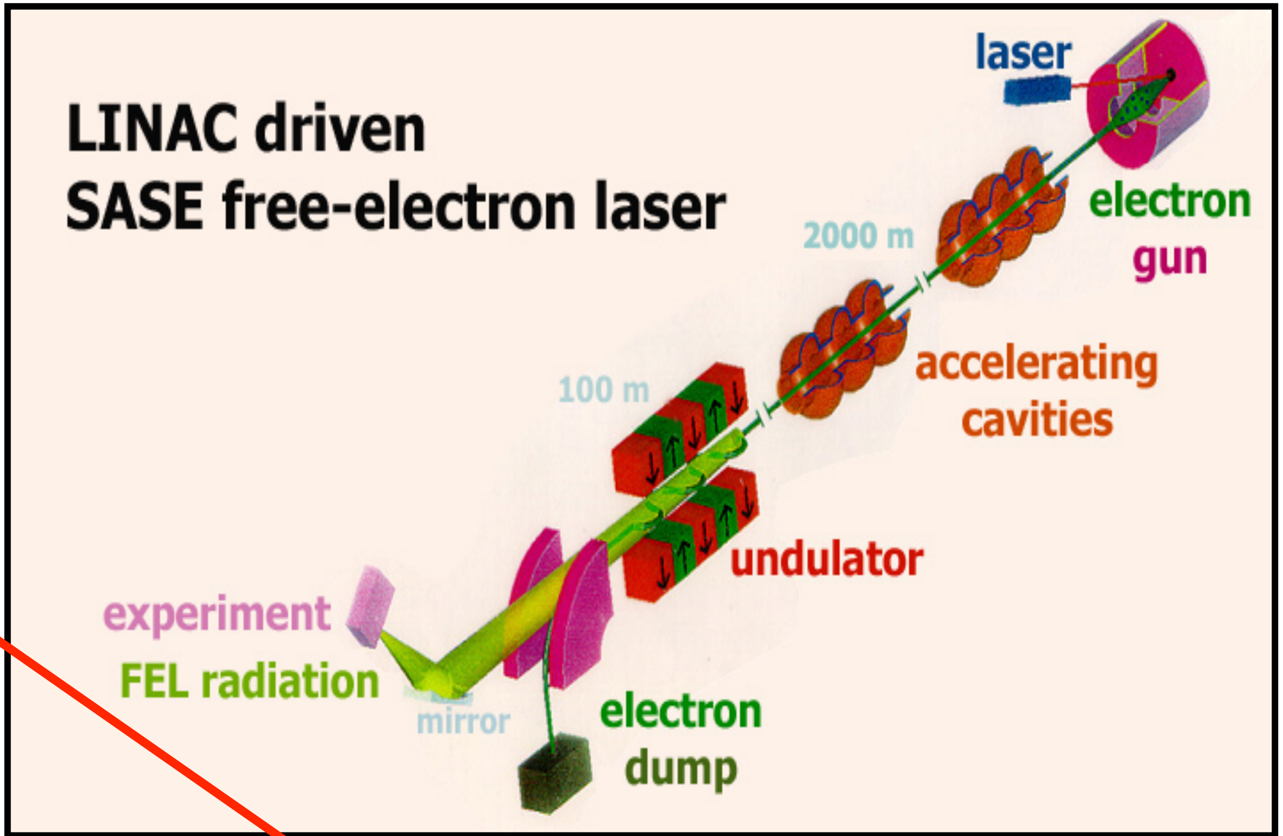




192 shaped pulses - 4 Mega Joules in 1 ns = 4 Petawatts peak power !!!

X-ray Lasers - Free Electron Lasers

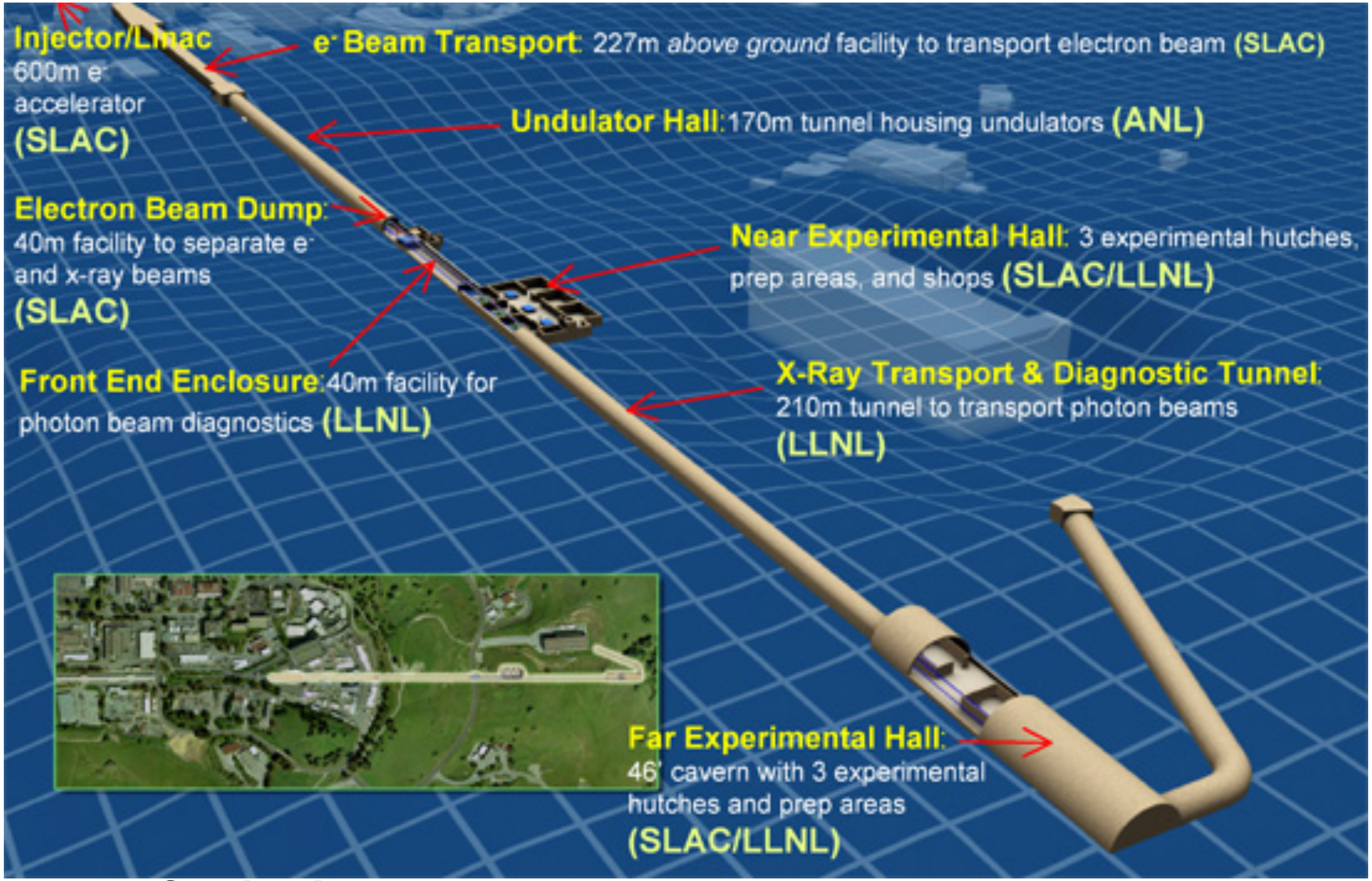




Hamburg FEL
Tunnel &
Experimental Hall

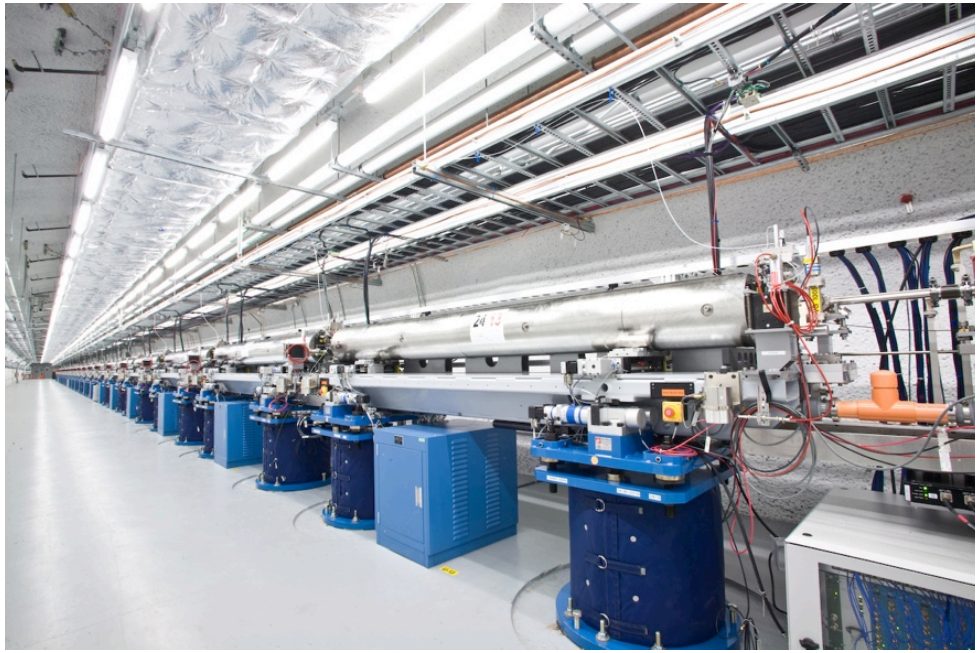
Big X-ray FEL - LCLS Stanford…

LINAC Coherent Light Source - LCLS



lcls.slac.stanford.edu

Big X-ray FEL - LCLS Stanford…

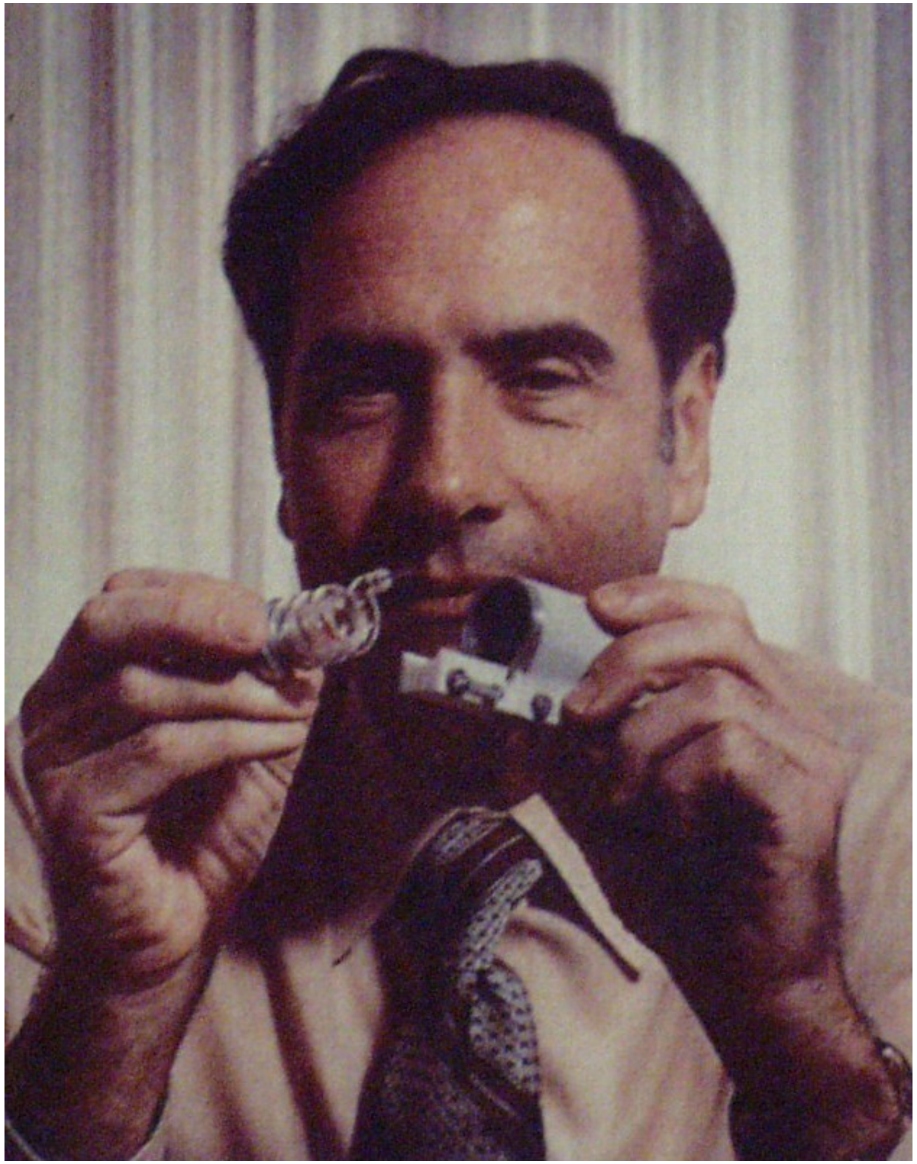


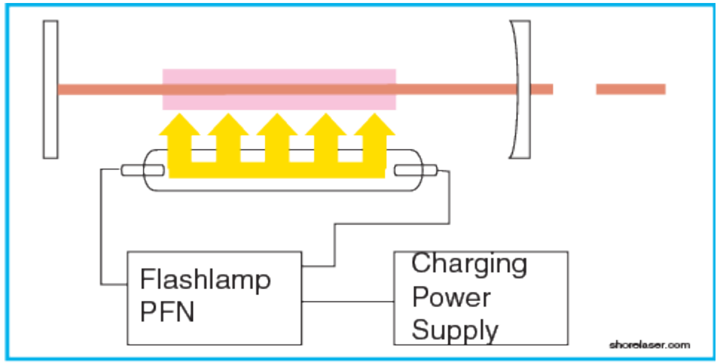
Electron Linear Accerator (LINAC) Tunnel – 4km long

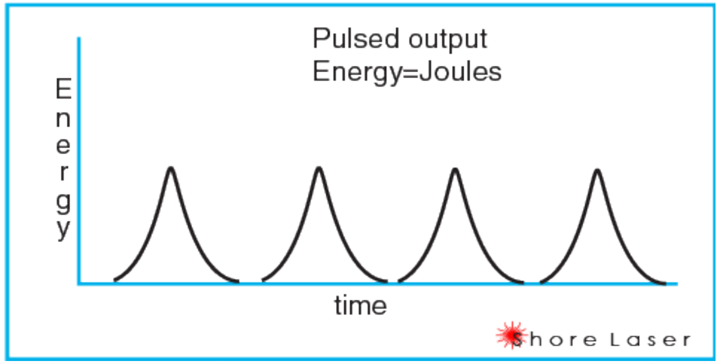
Undulators in which electron bunches create X-ray pulses

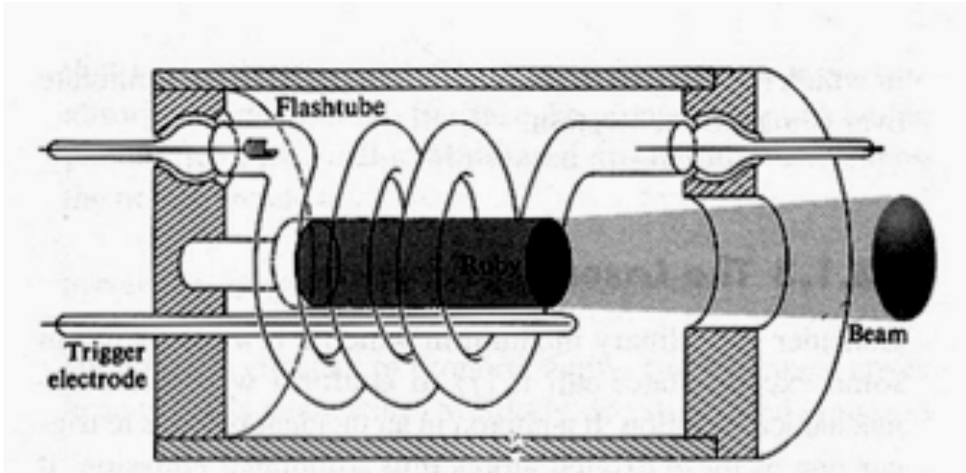
Nature Photonics 4, pp 641-647 (2010) /

How does a laser work ?









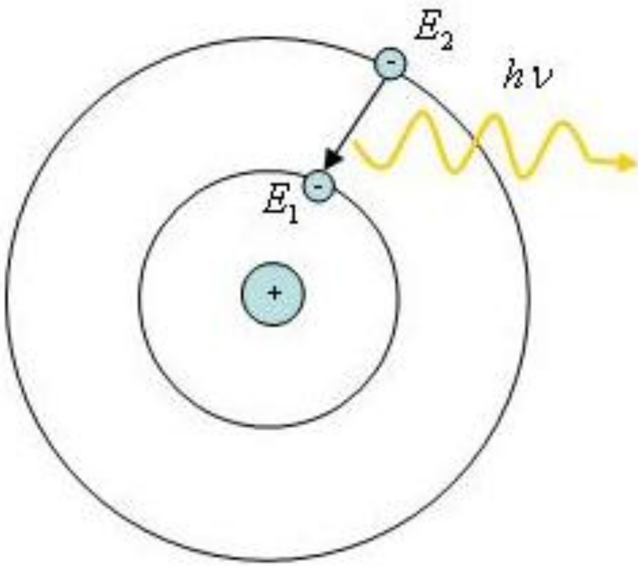
How does a laser work ?

Question: What is the origin of light ?
Answer: When matter (solid, liquid or gas) is heated up to high temperature it emits radiation in the form of light. In fact it is the individual atoms that make up the matter that emit light…..

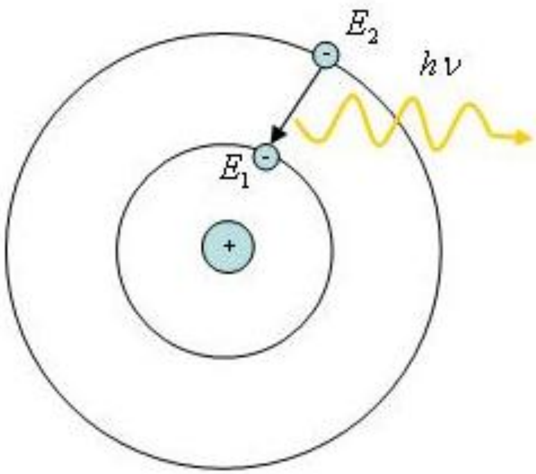
For example - when you light a fire the it is the carbon atoms in the coal that emit bright light……

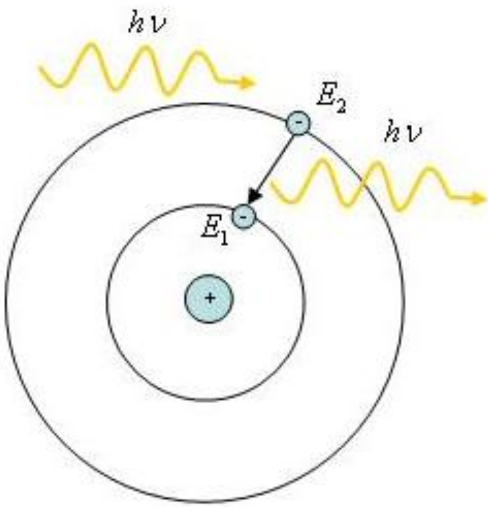
However - we must look to see how an atom emits light: *Spontaneous versus Stimulated Emission*

1. Every atom is composed of a ‘positively charged’ nucleus at its centre surrounded by electrons which ‘orbit’ the nucleus - like a mini-solar system.
2. The size of the orbit depending on how much energy the electron has, i.e., the most energetic electrons are furthest from the nucleus.
3. If an electron loses energy it drops down from a higher to a lower orbit and ‘emit’ the energy lost as a packet of light known as a ‘Photon’
4. This is the basic process by which atoms radiate light and is called ‘spontaneous emission’.

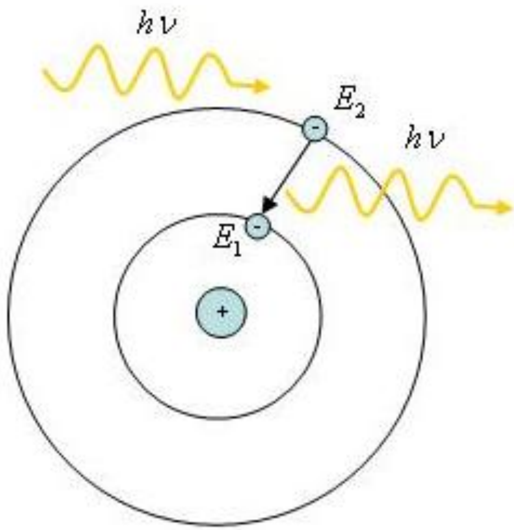


Now look at the picture below on the right hand side and compare with the original on the left hand side…

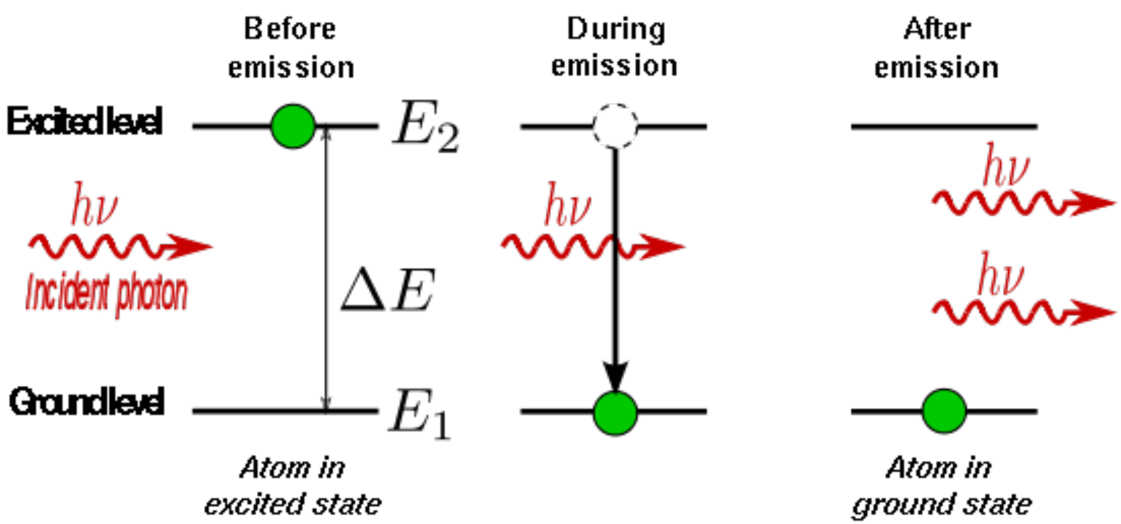




On the right hand side, a photon emitted from another atom (e.g., the one on the left hand side) causes the atom on the right hand side to emit a another photon - *this process is known as ‘stimulated emission’ and the result is ‘Light Amplification’….*



If an atom has an electron orbiting around the nucleus with an energy E_2 and it slows down so that its energy becomes E_1, then it will emit a 'photon' of energy E_2 - E_1. The wavelength of the light emitted can be calculated from:



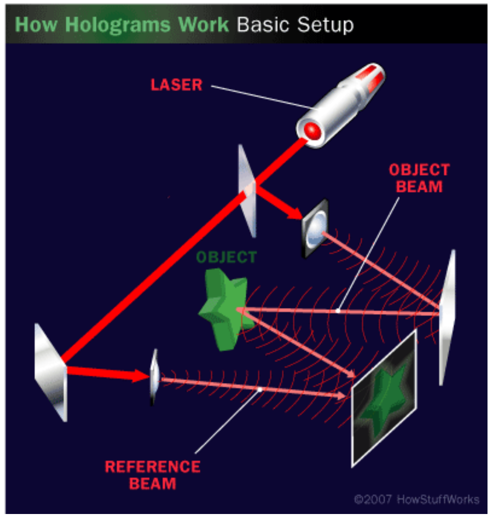
$$E_2 - E_1 = \Delta E = h\nu$$

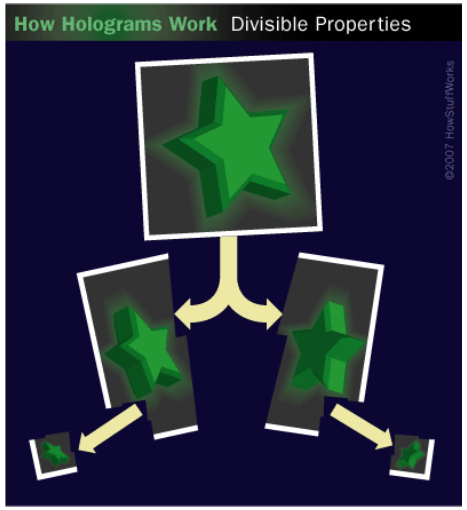
$$h\nu = \frac{hc}{\lambda} = E_2 - E_1$$

ν = frequency
λ =wavelength

How is laser light different to ordinary light from an ordinary bulb ?

1. It is collimated (it forms a parallel beam)
2. It is monochromatic (single colour)
3. It is coherent (so that you can make holograms)





What does PS407 entail ?

- Quantum (Optical) Electronics = Physics of Lasers and Physics with Lasers
  - Quantum description necessary (discrete energy levels, band structure, transition probabilities,...)
  - New “quantum” effects: e.g., quantum well (QW) lasers
  - Quantum optics

What does PS407 entail ?

- Applications of lasers:
  - “Old” effects with new tool (e.g. laser melting, laser drilling, laser machining,...)
- Unique properties of laser light
  - “New” effects with new tool: non-linear effects (second harmonic generation), four-wave mixing, stimulated processes (Raman, Brillouin) etc...

Course objectives: Lectures

- Physics of laser/laser light:
  - Theory of laser oscillation
  - Unique properties of laser light
  - Different types of lasers
  - Aspects of the interaction of laser light with matter
- Optical phenomena related to and made possible by laser radiation:
  - Electro-optics
  - Magneto-optics
  - Non-linear optics
  - Amplification

Course objectives: Projects

- Current technological developments in the field of **Photonics**:
  - **Medical lasers**
  - **Laser cleaning**
  - **Quantum cascade lasers**
  - **Fiber lasers**
  - **Ultrafast lasers: fs, as**
  - **Laser remote sensing**
  - **Laser communications**
  - **Laser TV**
  - **Many other applications!!!!**

Housekeeping

- Teaching methods
  - 2 to 3 Lectures/week
  - Tutorial will focus on numerical problems
- Assessment
  - 2 Class Tests: 20% of final mark
  - End-of-module exam: general + numerical questions on lecture material 80%

Housekeeping

- Propose to make Friday a Zoom Lecture
- No research/admin absences planned (yet)

The laser: A driver for new science and applications

- Development/advancement of fundamental areas of physics:
  - Atomic and molecular physics
  - Quantum mechanics / Vacuum-QED
  - Relativity
- Development/advancement of applied areas of physics:
  - Laser spectroscopy
  - Laser sensing
  - Etc…

The laser: A driver for new science and applications

- Biology
- Chemistry
- Medicine
- Technological revolution in the field of (tele)communications (optical communications)

Recent achievements of the laser

www.nobelprize.org

Recent Nobel Prizes in Physics:

2012 Serge Haroche and David J. Wineland
“..for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems..”

2009 Charles Kuen Kao, Willard Boyle, George E. Smith: One half awarded to Charles Kuen Kao "for groundbreaking achievements concerning the transmission of light in fibers for optical communication",the other half jointly to Willard S. Boyle and George E. Smith "for the invention of an imaging semiconductor circuit – the CCD sensor…”

2005: R. Glauber, J. Hall, T. Hansch: “…for their contributions to the development of laser-based precision spectroscopy…”

2001: Cornell, Ketterle, Wiemann: “for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms…”

Recent Nobel Prizes in Chemistry:

2014 Eric Betzig, Stefan W. Hell and William E. Moerner: "for the development of super-resolved fluorescence microscopy"

2002: K. Tanaka, J. Fenn: “...for their development of soft desorption ionisation methods for mass spectrometric analyses of biological macromolecules"

1995: A. Zewail: For his studies of the transition states of chemical reactions using femtosecond laser spectroscopy

Recent achievements of the laser

www.nobelprize.org

- http://www.nobelprize.org/educational/physics/laser/
- 2012 Physics Prize: Serge Haroche and David Weinland

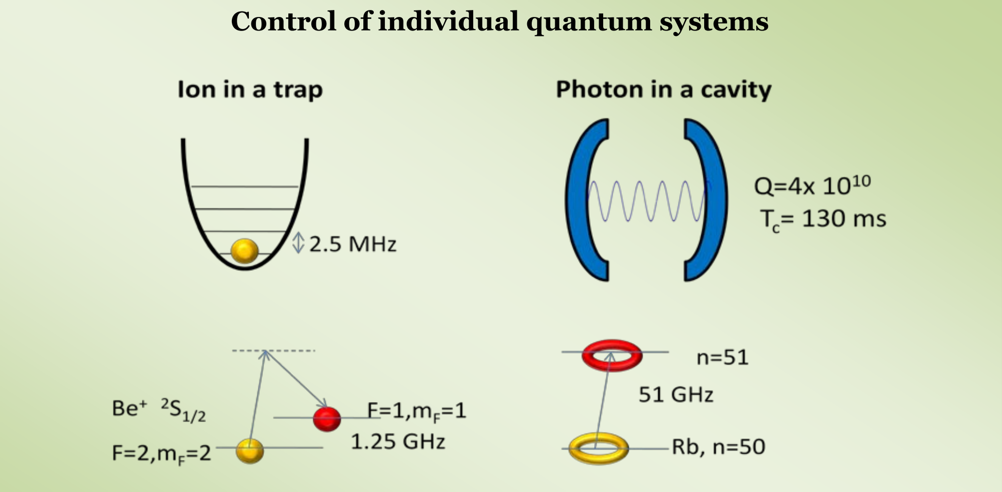


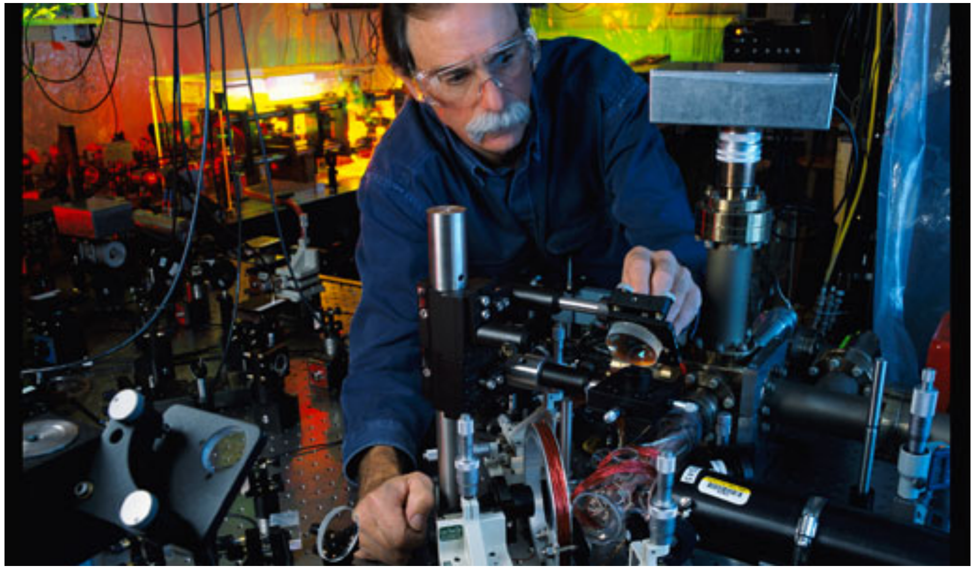
Fig. 1: Illustration of the two types of experiments discussed in this scientific background: On the left, an ion is captured in a harmonic trap. Its quantum state (both its internal state and its motion) is controlled by interaction with laser pulses as exemplified for the case of Be+. On the right, a photon is (or several photons are) trapped in a high-Q microwave cavity. The field state is measured and controlled by interaction with highly excited Rb atoms.

MEASURING AND MANIPULATING INDIVIDUAL QUANTUM SYSTEMS

2012 Nobel Prize Winners…..

Serge Haroche

David Wineland



€€€€€€$$$$$$££££££¥¥¥¥¥¥¥¥¥
Lasers mean big money!

- New technologies based on lasers are being developed at a fast rate.
- This, in turn, drives new theoretical developments which will be used in the future as the basis for new technologies.
- Thus, lasers and their applications are currently the main products of an exploding market!

PHOTONICS

The Field of quantum optics/electronics is only recent. What are the major milestones?

1917 – A. Einstein introduces the process of stimulated emission.
1926 – Ch. Raman discovers the Raman Effect in liquids
1948 – D. Gabor (GB) records the first hologram
1954 – N. Basov/A.Prokhorov (USSR) and, independently, Ch. Townes (USA) built the first MASER (Microwave Amplification by Stimulated Emission of Radiation).
1958– A. Schalow and Ch. Townes show theoretically that stimulated emission could also be used to amplify optical radiation.
1960 – T.H. Maiman builds the first solid state laser Ruby laser (USA). A. Javan et al build the first gas laser -employs a mixture of helium and neon gases).

Major milestones continued…. Key Paper….

PHYSICAL REVIEW VOLUME 112, NUMBER 6 DECEMBER 15, 1958

Infrared and Optical Masers

A. L. Schawlow and C. H. Townes*
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received August 26, 1958)

The extension of maser techniques to the infrared and optical region is considered. It is shown that by using a resonant cavity of centimeter dimensions, having many resonant modes, maser oscillation at these wavelengths can be achieved by pumping with reasonable amounts of incoherent light. For wavelengths much shorter than those of the ultraviolet region, maser-type amplification appears to be quite impractical.
Although use of a multimode cavity is suggested, a single mode may be selected by making only the end walls highly reflecting, and defining a suitably small angular aperture. Then extremely monochromatic and coherent light is produced. The design principles are illustrated by reference to a system using potassium vapor.

Major milestones continued…. Key Paper….

Letters to Nature

Nature 187, 493-494 (6 August 1960) I doi:10.1038/187493a0
Stimulated Optical Radiation in Ruby

T. H. MAIMAN

1. Hughes Research Laboratories, A Division of Hughes Aircraft Co., Malibu, California.

Abstract
Schawlow and Townes1 have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan2 and Sanders3 have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å. ; the active material used was ruby (chromium in corundum).

Major milestones continued….

1961 – P.A. Franken (USA); 2nd harmonic generation.
1962 – N. Bloembergen (USA) develops the theory of non-linear optics
Generation of coherent light using parametric oscillations
1962-63 – Development of first semiconductor lasers in USA and USSR
1963 – Photon (Quantum) optics (USA)
1964 – Self-focusing of laser light (USA)
1964 – A. Kastler (France) optical pumping method for generation of short-wave coherent radiation. Goldfinger movie!
1964 – N. Basov (USSR) proposes to create a high temperature plasma with a laser beam (nuclear fusion).
1970's – Ultrashort laser pulses- mode locking; pico 10^{-12} s and femto 10^{-15} s pulses
1980's – Pulse chirping. Considerable developments in the physics of the semiconductor laser result in High-rate optical fiber communication systems.
2000 - Quantum-well semiconductor lasers; quantum dots/wires; Superlattices; Optical fiber amplifiers
Photon switching; Integrated optoelectronic circuit
Quantum computing; free-electron lasers; tunable solid-state laser
2003 Attosecond laser (10^{-18} s) (pulse shorter than 1 cycle of visible light)
2007 Extreme-UV Free Electron Laser FLASH - Hamburg
2010 X-ray Free Electron Laser LCLS - Stanford

- Pulse shorter than 1 cycle of visible light ? Can we work it out?

$$c = \frac{\lambda}{T} \rightarrow T = \frac{\lambda}{c}$$

c speed of light, λ wavelength, T period

$$T = \frac{\lambda}{c} = \frac{550 \times 10^{-9}\ \text{(green)}}{3 \times 10^{8}} \approx 2 \times 10^{-15}\ \text{s} \equiv 2\ \text{fs}$$

Structure of Course

I. Wave Optics- Electromagnetic Optics-Polarisation and Crystal Optics
II. Beam Optics: Gaussian beams
III. Optical Resonator
IV. Interaction of Photons with atoms, molecules, solids. Line shapes
V. The laser amplifier: Examples of lasers (semiconductor, gas, glass lasers)
VI. Theory of the laser oscillation: Laser oscillator
VII. Pulsed Lasers (Q-switching, mode-locking)
VIII. Non-linear optics, e.g. Second Harmonic Generation (contents may vary)

Reading List (Not exhaustive !!!)

- Quantum Electronics, A .Yariv (Wiley)
- Optical Electronics, A. Yariv (Holt, Saunders Publishing)
- Laser Fundamentals, W. Silfvast (Cambridge U. Press)
- Optoelectronic Semiconductor Devices, D. Wood (Prentice Hall)
- **Fundamentals of Photonics, B.E. Saleh and M. Teich (Wiley, 2nd edition, 2007)**
- Atomic Physics of Lasers, Derek Eastham, (Taylor and Francis)
- Lasers, A. Siegman (University Science Books)

- Electronic notes in pdf: strictly copy of material used in lectures
- Available on LOOP and from my webpage - www.physics.dcu.ie/~jtc
- I will communicate with you via email
- My email is john.costello@dcu.ie
- Office after N233. Down a corridor on the 2nd floor……