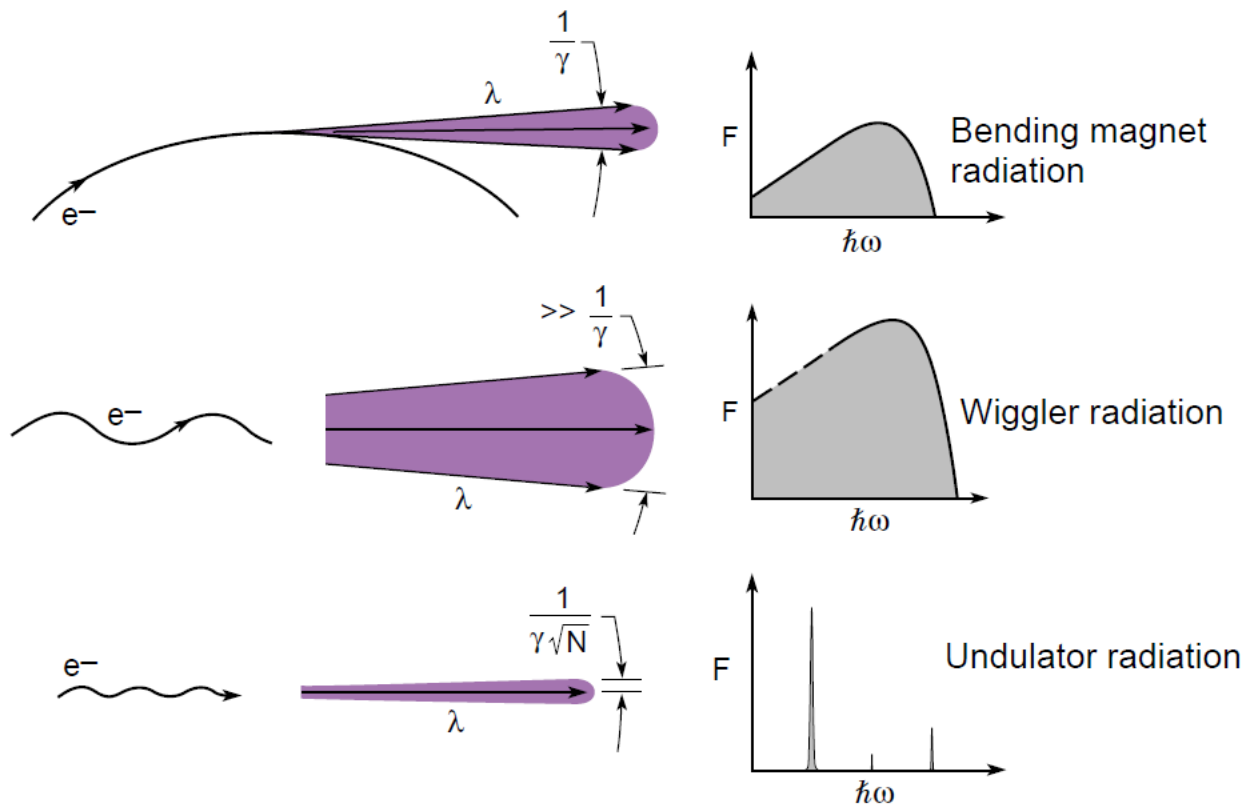
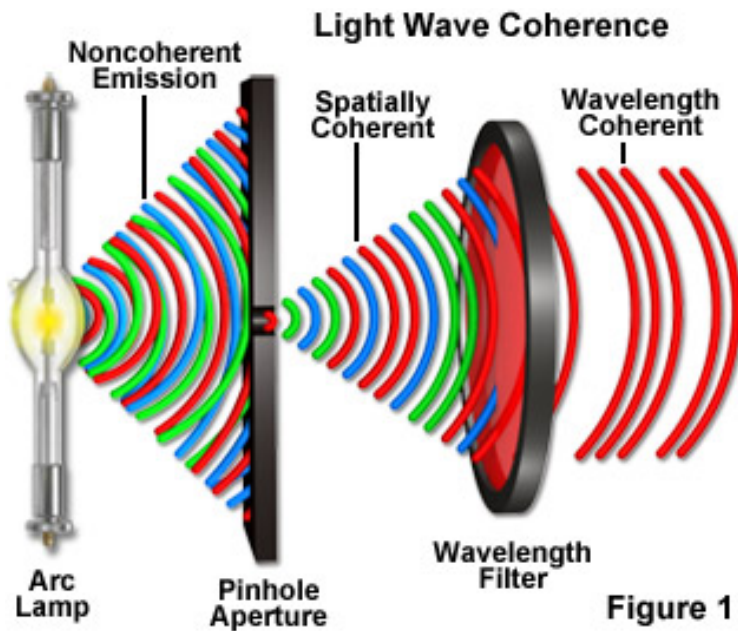


Comparison



Coherence

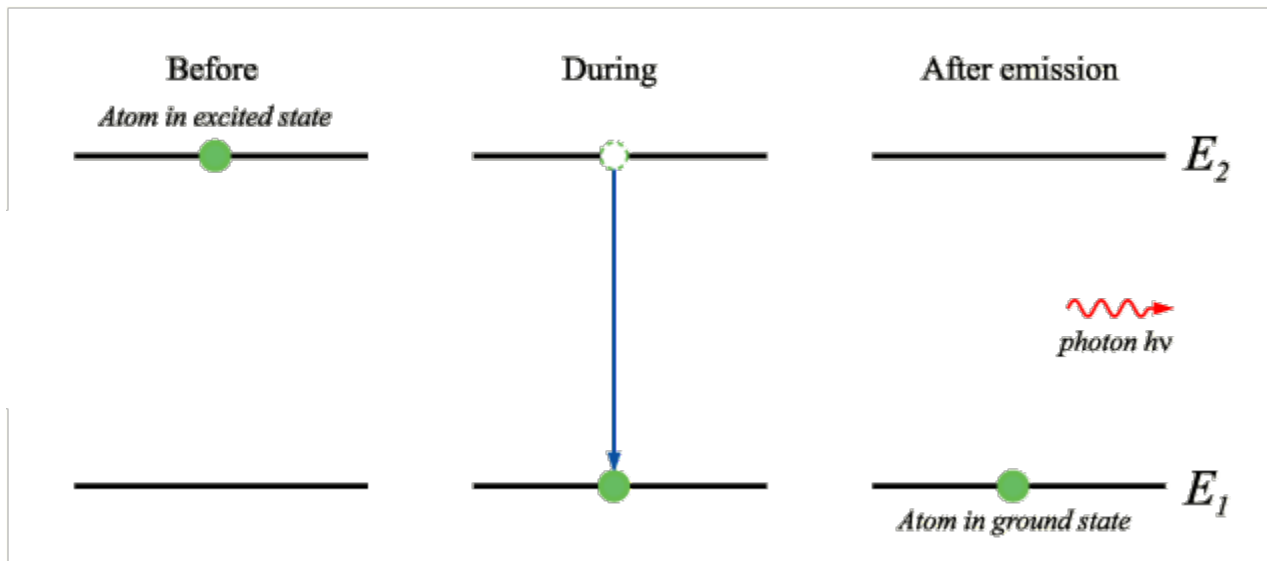




Quantum Lasers

A (very) brief introduction

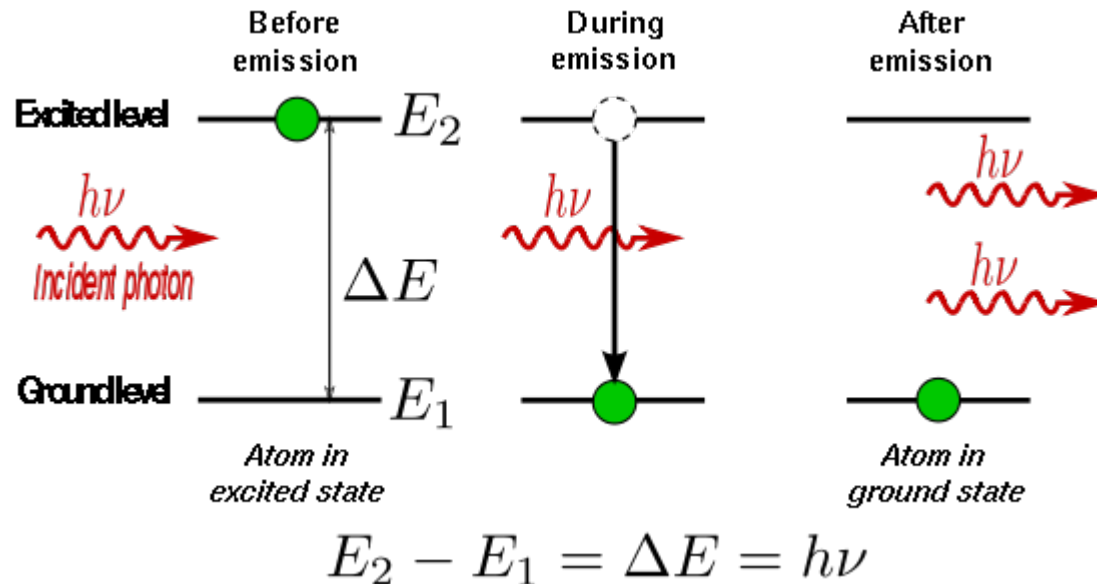
Spontaneous Emission



- ▶ When this energy is delivered in the form of an electromagnetic (em) wave, the process is called spontaneous (or radiative) emission

$$h\nu_0 = E_2 - E_1$$

Stimulated emission



- ▶ The atom is initially found in level 2 and an em wave of frequency $\nu = \nu_0$ is incident on the material
- ▶ Since this wave has the same frequency as the atomic frequency, there is a finite probability that this wave will force the atom to undergo the transition.
- ▶ In this case the energy difference is delivered in the form of an em wave that adds to the incident wave.

Maser vs Laser

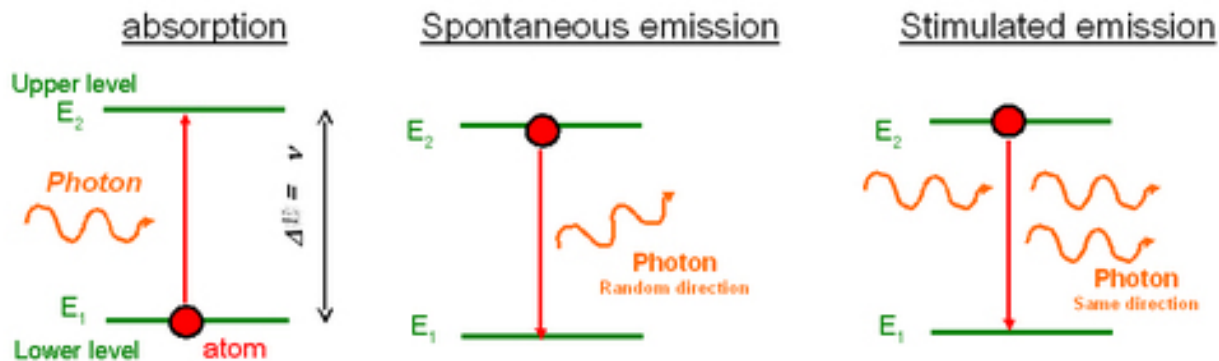
$$h\nu_0 = E_2 - E_1$$

- ▶ If the frequency is in the microwave range we have a MASER=**Microwave Amplification by Stimulated Emission of Radiation**
- ▶ If this frequency is in the optical region, we have a LASER=**Light Amplification by Stimulated Emission of Radiation**

Main difference

- ▶ There is a fundamental difference between the spontaneous and stimulated emission processes.
- ▶ In the case of spontaneous emission, atoms emit an em wave that has no definite phase relation to that emitted by another atom.
- ▶ Furthermore the wave can be emitted in any direction.
- ▶ In the case of stimulated emission, since the process is forced by the incident em wave, the emission of any atom adds in phase to that of the incoming wave and in the same direction

Population



- ▶ N_i be the number of atoms (or molecules) per unit volume that at time t occupy a given energy level.
- ▶ N is called the population of the level.

Einstein's coefficients

$$\left(\frac{dN_2}{dt}\right)_{sp} = -AN_2$$

Spontaneous emission

$$\left(\frac{dN_2}{dt}\right)_{st} = -W_{21}N_2$$

Stimulated emission

$$W_{21} = \sigma_{21}F$$

$$\left(\frac{dN_1}{dt}\right)_a = -W_{12}N_1$$

Absorption

$$W_{12} = \sigma_{12}F$$

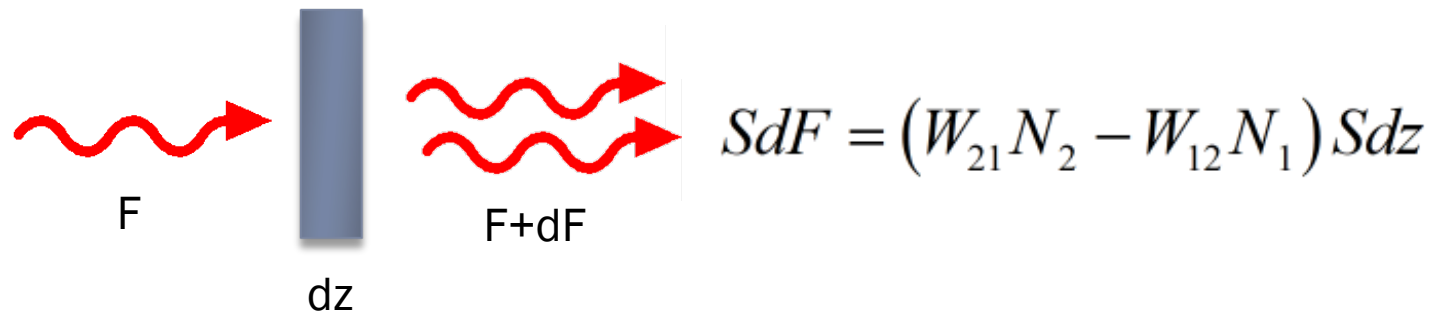
Relations between coefficients

- ▶ if the two levels are nondegenerate, one has $W_{21} = W_{12}$ and thus $\sigma_{21} = \sigma_{12}$.
- ▶ If levels 1 and 2 are g_1 -fold and g_2 -fold degenerate, respectively, one then has:

$$g_2 W_{21} = g_1 W_{12}$$

$$g_2 \sigma_{21} = g_1 \sigma_{12}$$

Amplifier or absorber



$$dF = \sigma_{21}F \left[N_2 - \left(\frac{g_2 N_1}{g_1} \right) \right] dz$$

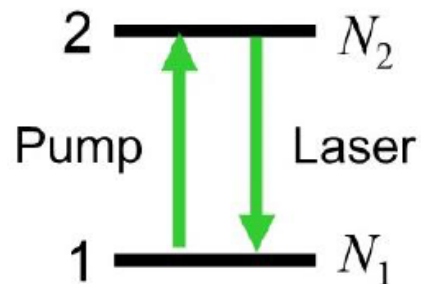
- ▶ >0 Amplifier
- ▶ <0 Absorber

Population inversion

$$\frac{N_2^e}{N_1^e} = \frac{g_2}{g_1} e^{-\frac{E_2 - E_1}{KT}}$$

- ▶ In thermal equilibrium the material acts like an absorber.
- ▶ If we are able to force the material to act like an amplifier it means that we have reached the population inversion
- ▶ A medium in which this population inversion is achieved is called active medium.

How to have population inversion?



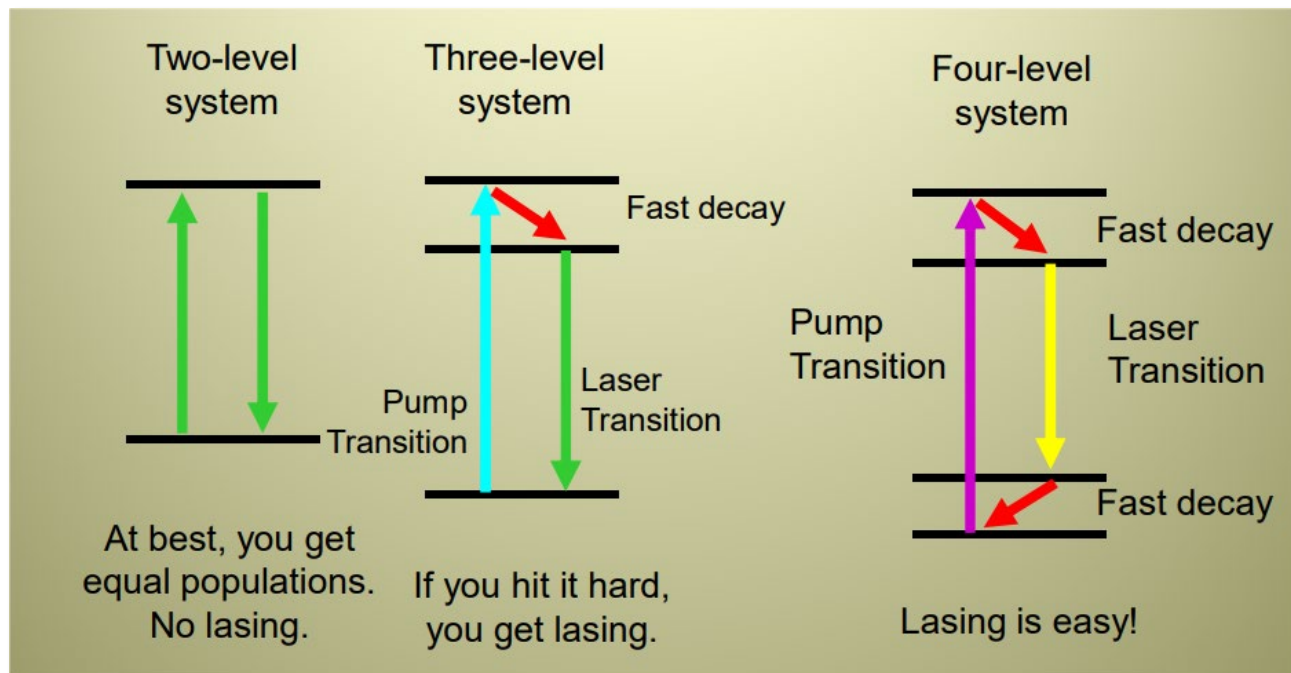
Rate of change of population \propto population density \times pumping rate

Absorption & stimulated emission equally likely

Best we can do is $N_2 = N_1$ - no population inversion in 2 level laser

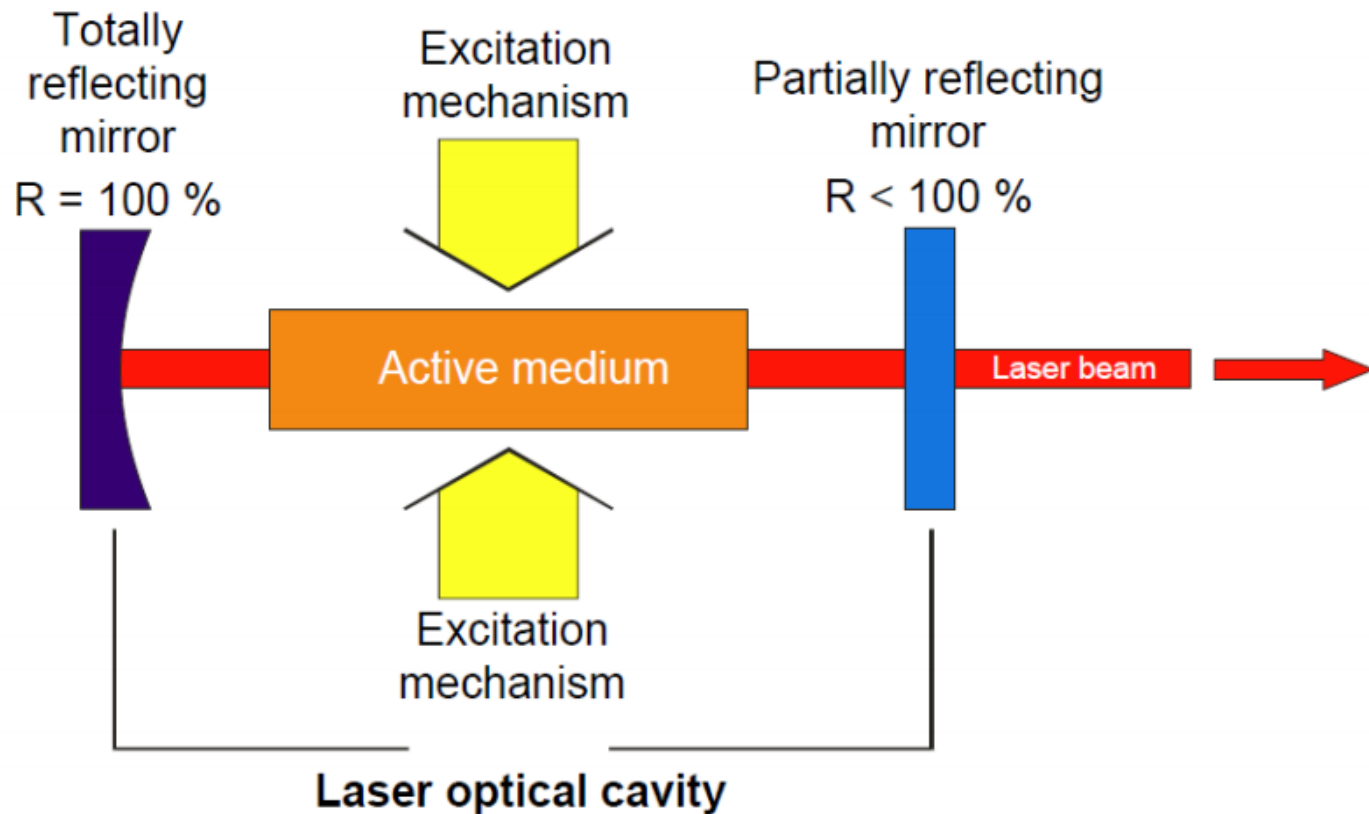
With just two levels, 1 and 2, it is therefore impossible to produce a population inversion

3 and 4 levels lasers



- In a 4 levels system there is always a complete inversion of the population

Basic scheme



Optical cavity

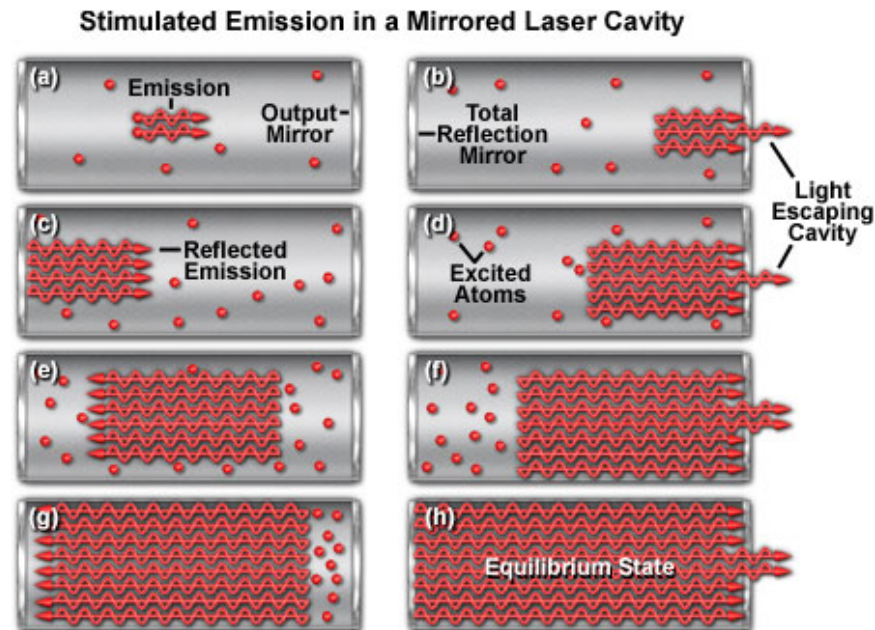


Figure 1

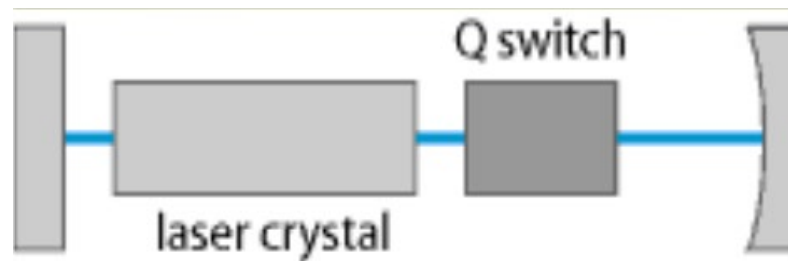
- Pump gain medium to upper level
- A photon decays spontaneously & stimulates more emission
- The photons bounce back and forth along the cavity if the number of photons emitted each round trip exceeds losses (mirrors etc.) laser is above threshold
- One of the mirrors allows a small amount of this light out laser output!
- Laser output controlled by gain of medium and longitudinal & transverse modes of cavity

Output

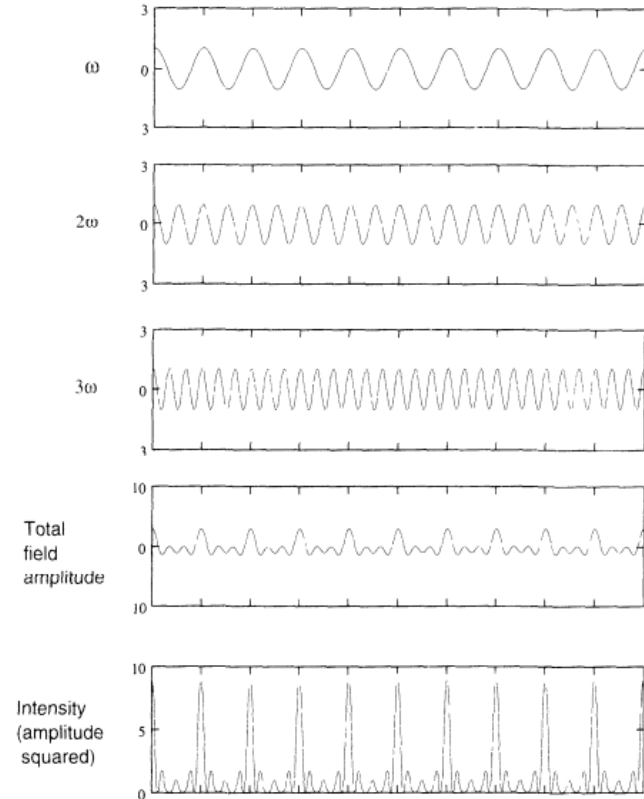
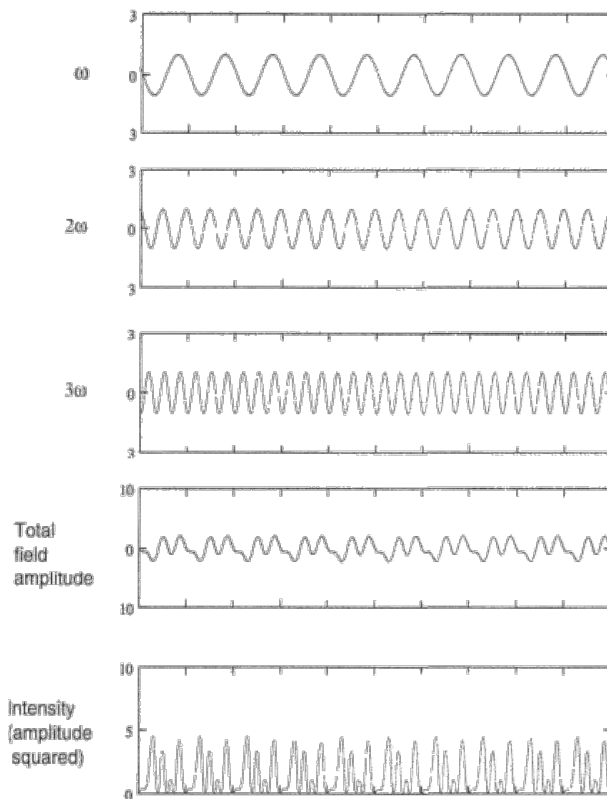
- ▶ Characteristics that affect laser performance are the power output and mode of emission - continuous wave, pulsed, Q-switched or Mode -locked lasers.
- ▶ **CW laser** - emits a continuous beam of light as long as medium is excited.
- ▶ **Pulsed laser** - emit light only in pulses- from femtoseconds to second
 - ▶ Q-switched laser-pulses from micro to nanosecond are produced
 - ▶ Mode-Locked laser -pulses from pico to femtoseconds are produced

Q switch

- ▶ Q-switching is a way of obtaining short - from a few nano - seconds to few tens of nano -seconds – powerful - from a few megawatts to few tens of megawatts- pulses of laser
- ▶ The active medium is excited without feedback -by blocking the reflection from one of the end mirrors of the cavity
- ▶ The end mirror is then suddenly allowed to reflect
- ▶ Suddenly applied feedback causes a rapid population inversion of the lasing levels
- ▶ Results in a very high peak power output pulse of short duration



Mode locking



- ▶ locking together the phases of all oscillating axial laser modes having slightly different frequencies.
- ▶ Interference between these modes causes the laser light to be produced as a train of pulses

Type of lasers

- ▶ Gas lasers:
 - ▶ Usually electrically pumped
 - ▶ Wide range of wavelengths
 - ▶ Low gain
- ▶ Liquid lasers
 - ▶ Solution of complex organic dyes
 - ▶ Widely tunable
- ▶ Solid state lasers
 - ▶ Widest class of laser systems
 - ▶ Lasing ion doped in crystalline host Nd:YAG , Ti:sapp
 - ▶ Ion in glass Nd:glass
 - ▶ Fibre lasers Er , Yb in glass
- ▶ Semiconductor diode lasers

Gas lasers

Probably widest range of wavelengths
uv to infrared.

- ▶ Helium neon –HeNe red (632.8nm)
gas laser.
- ▶ Pumped by electrical discharge.



Uv excimer lasers –100 –300nm

- Photolithography
- Pumps for chemical reactions
- Poisonous gases –chlorine, fluorine!

CO₂lasers (10.6mm).

- Industrial & medical applications.



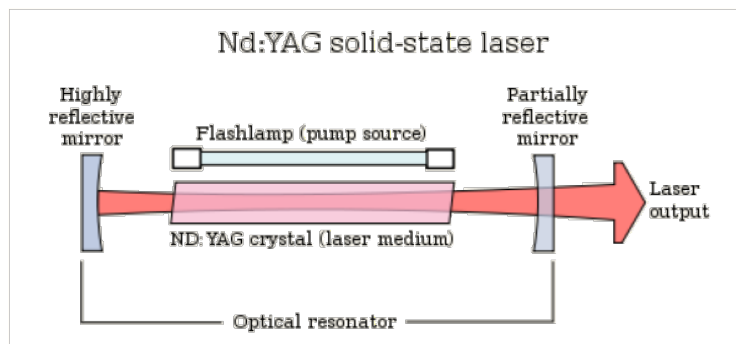
Solid state lasers

Most important class of lasers: many lasers have solid gain media:

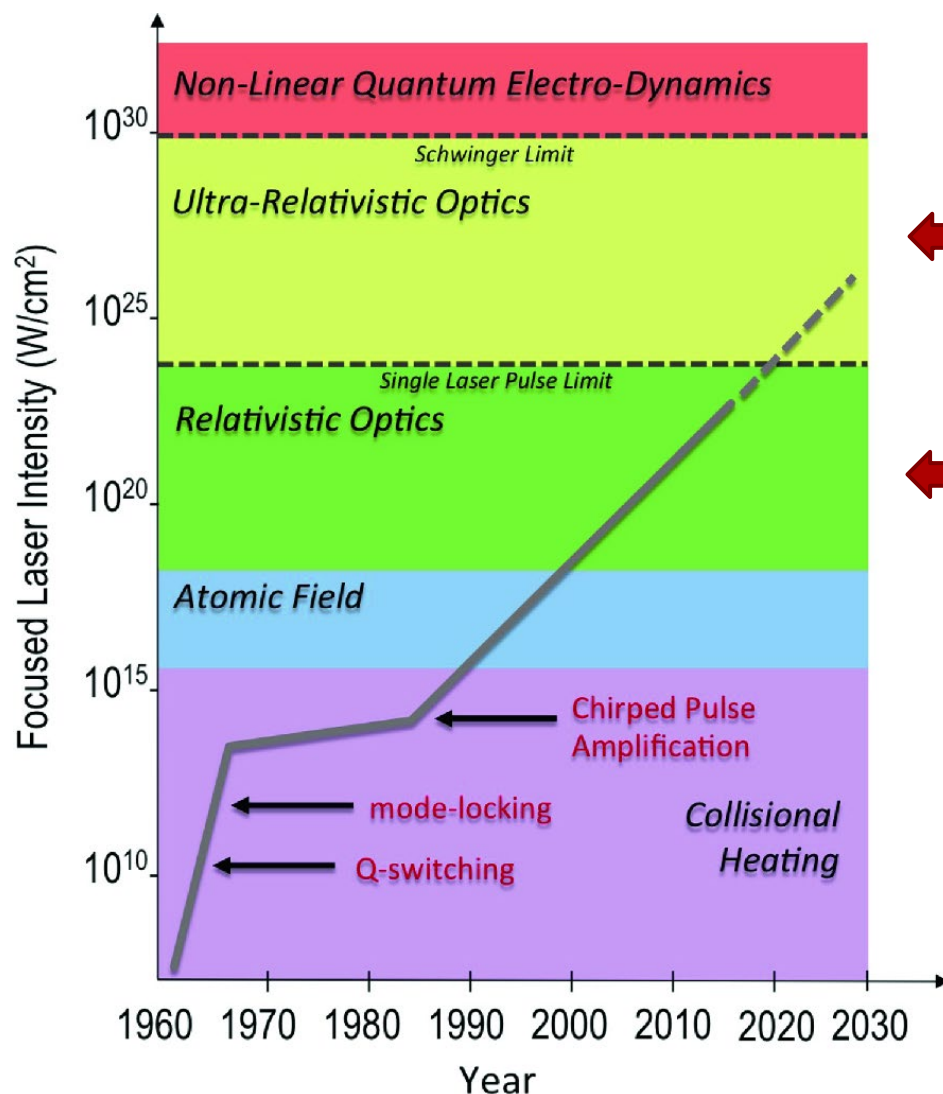
- ▶ solid state generally means lasing ions doped into crystalline/glass host, e.g. Ti:sapp, Nd:YAG, Nd:glass

Other solid-state lasers referred to separately:

- ▶ Semiconductor diode lasers (often used to pump other lasers)
- ▶ Fibre lasers –usually rare earth ions e.g. Er, Yb, doped into glass.



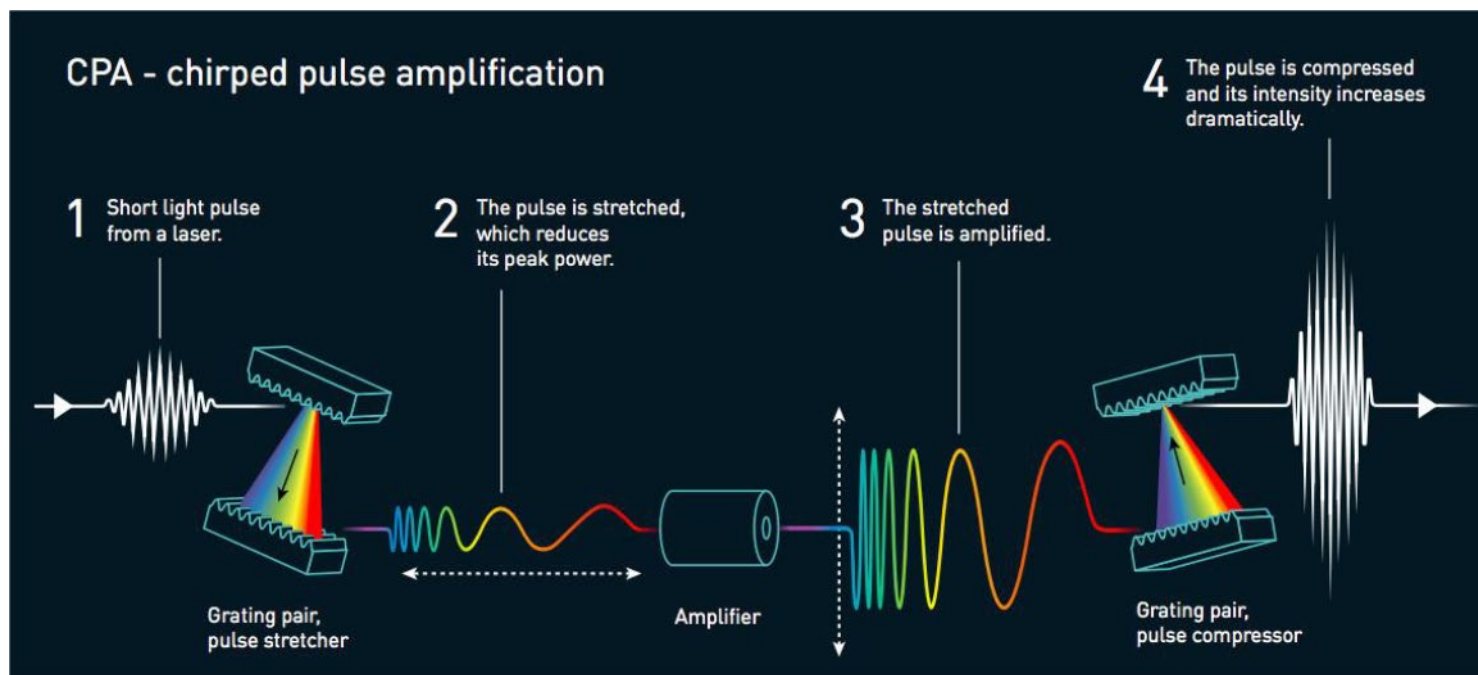
High power



← Also ions are relativistic

← Electron interacting with laser are relativistic

Chirped Pulse Amplification



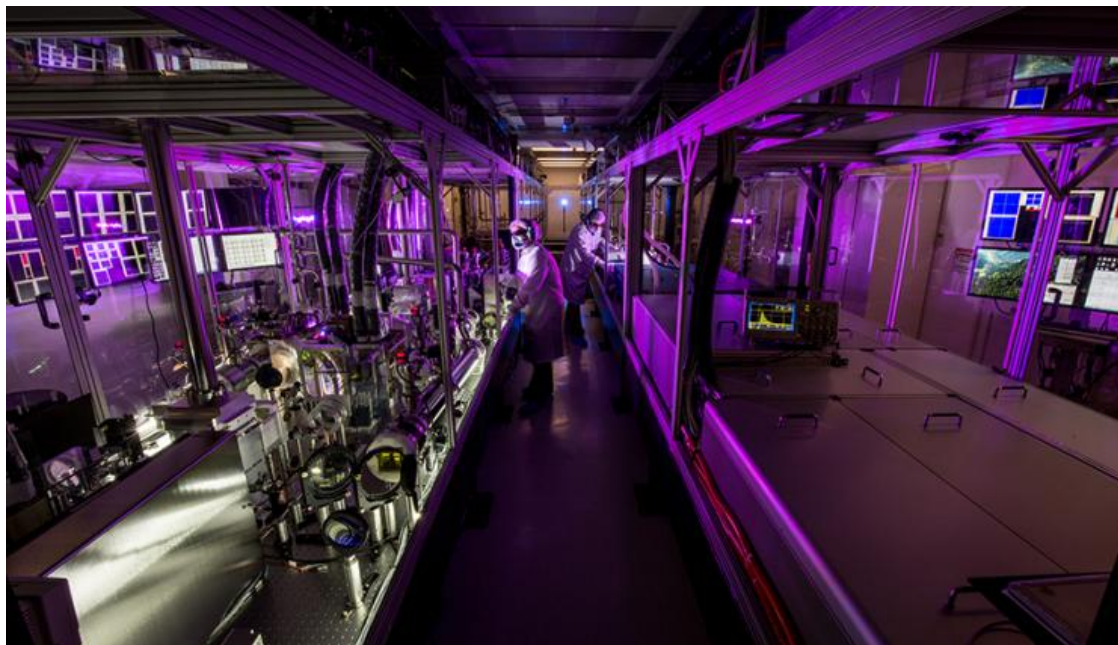
Nobel prize in Physics



State of art

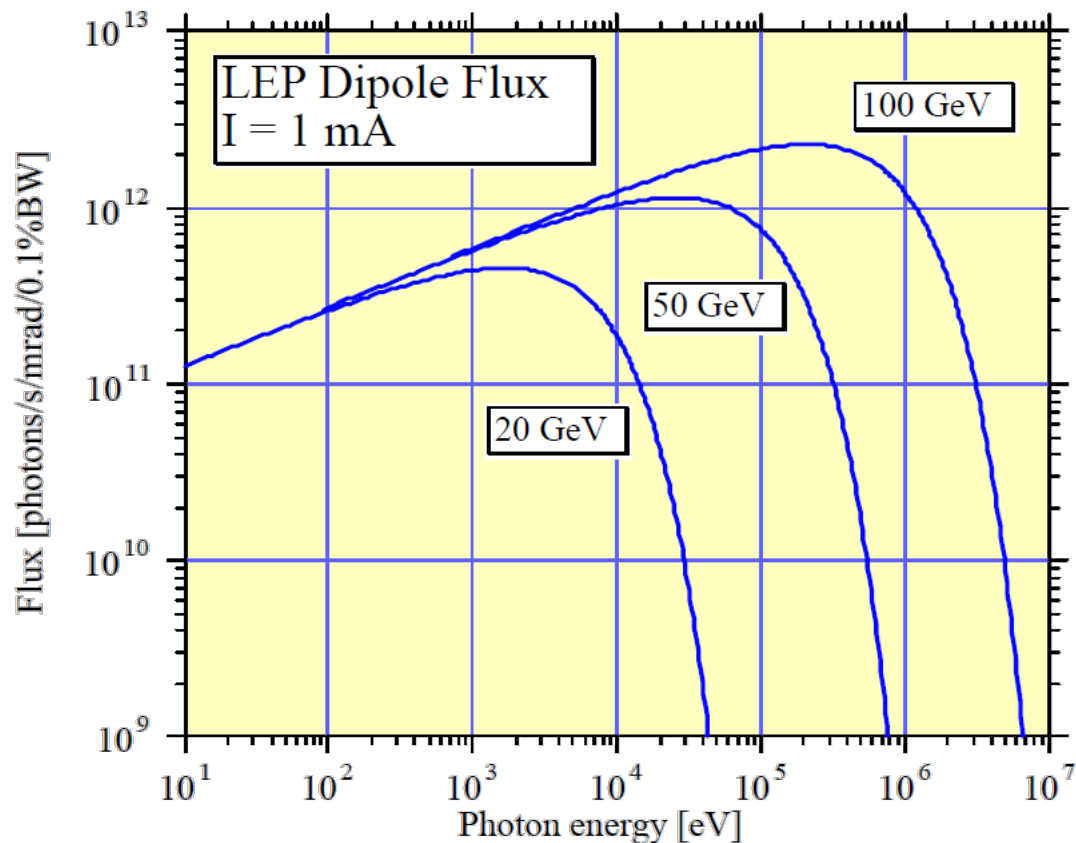
- ▶ **CPA hugely successful – operational 10 PW laser!**
- ▶ **10,000,000,000,000,000 W**
- ▶ Expensive
- ▶ Low repetition rate –1 shot/hr, /min, /s –still too slow
- ▶ So low *average* power
- ▶ BELLA laser at LBNL
- ▶ Peak power $\sim 40\text{J}/40\text{fs} = 1\text{PW}$
- ▶ Average power $40\text{J/s} = 40\text{W}$

- ▶ Efficiency
- ▶ BELLA uses 130kW electrical power
- ▶ 0.03% wall plug efficiency



Remember this slide

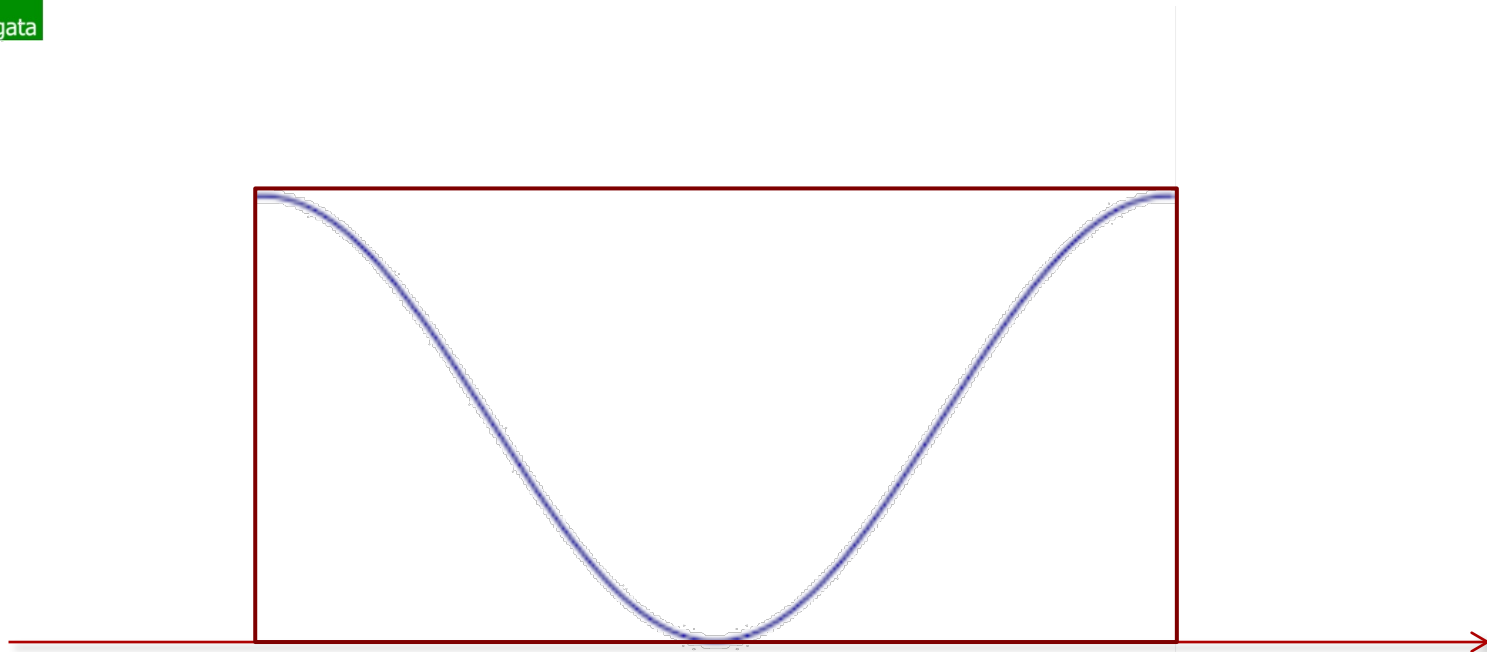
No energy
dependence at
long wavelength



Coherent emission due to bunching!

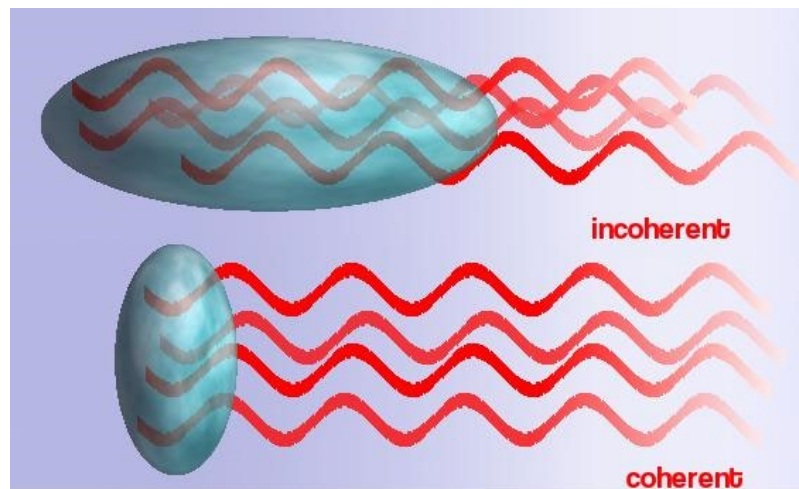
- ▶ Synchrotron radiation is emitted into a broad spectrum with the lowest frequency equal to the revolution frequency and the highest frequency not far above the critical photon energy.
- ▶ At low photon frequencies we may observe an enhancement of the synchrotron radiation beyond intensities predicted by the theory of synchrotron radiation as discussed so far.
- ▶ For photon wavelengths equal and longer than the bunch length, we expect therefore all particles within a bunch to radiate coherently and the intensity to be proportional to the square of the number N_e of particles rather than linearly proportional as is the case for high frequencies. This quadratic effect can greatly enhance the radiation since the bunch population can be from 10^8 – 10^{11} electrons.

Bunch length=wavelength



- ▶ All the particles emit radiation at different phases.
- ▶ All the phases are emitted.
- ▶ The overall radiation intensity is zero!

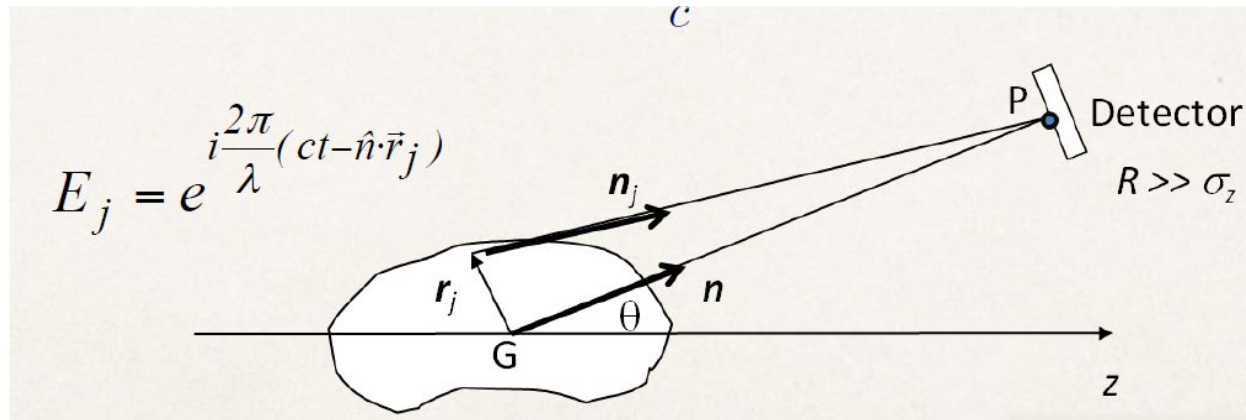
Coherent emission II



$$I_{tot}(\lambda) = I_{sp} [N + N(N - 1)F_{long}(\lambda)]$$

- ▶ Generally such radiation is not emitted from a storage ring beam because radiation with wavelengths longer than the vacuum chamber dimensions are greatly damped and will not propagate along a metallic beam pipe.
- ▶ Much shorter electron bunches of the order of 1-2 mm and the associated coherent radiation can be produced in linear accelerators where a significant fraction of synchrotron radiation is emitted spontaneously as coherent radiation.

Form factor



- the total field is given by the sum of the fields of each of the N particles and the total intensity can be written, in the limit of the Fraunhofer scalar theory, as

$$I_{tot}(\omega) = I_{sp}(\omega) \sum_{j,k} E_j E_k^* \quad I_{tot}(\omega) = I_{sp}(\omega) \left(N + \sum_{j \neq k}^N \exp \left(i \frac{\omega}{c} \hat{n} \cdot (\vec{r}_j - \vec{r}_k) \right) \right)$$

$$I_{tot}(\omega) = I_{sp}(\omega) [N + N(N-1)F(\omega)] \quad F(\omega) = \left| \int_{-\infty}^{\infty} dz S(z) e^{i \frac{\omega}{c} z} \right|^2$$



Free Electron Laser

Principles of operation

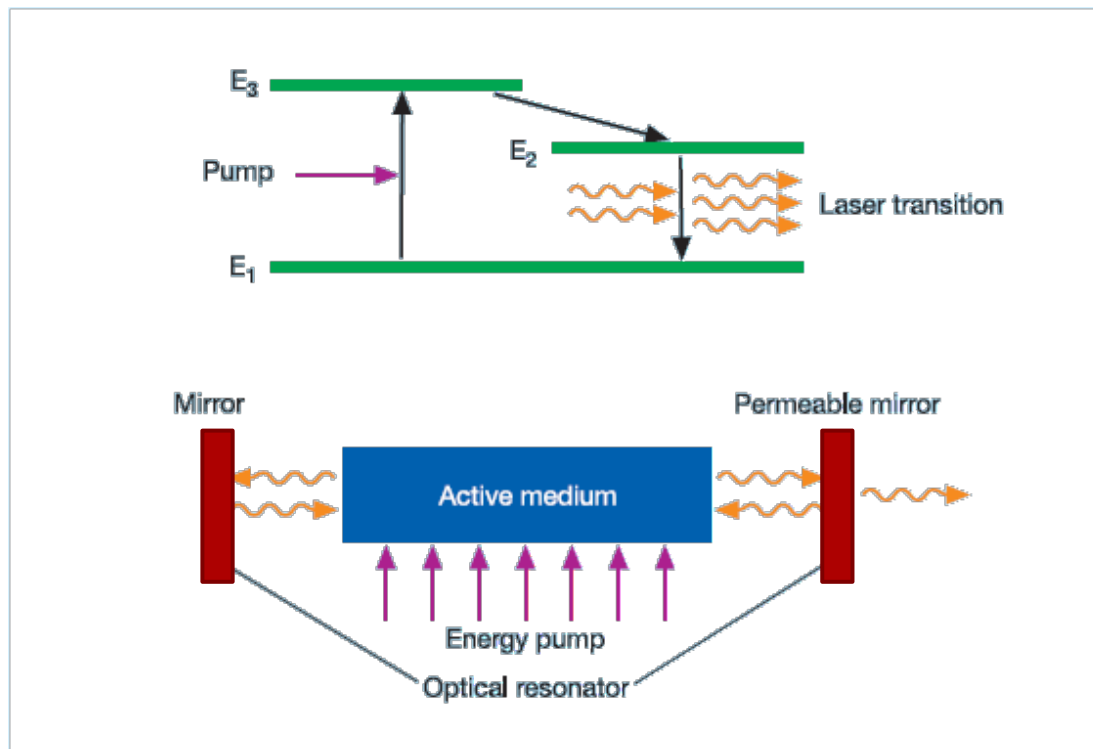
Bibliography

- ▶ Peter Schmuser, Martin Dohlus, Jorg Rossbach, "Ultraviolet and Soft X-Ray Free-Electron Lasers", Springer

Three steps

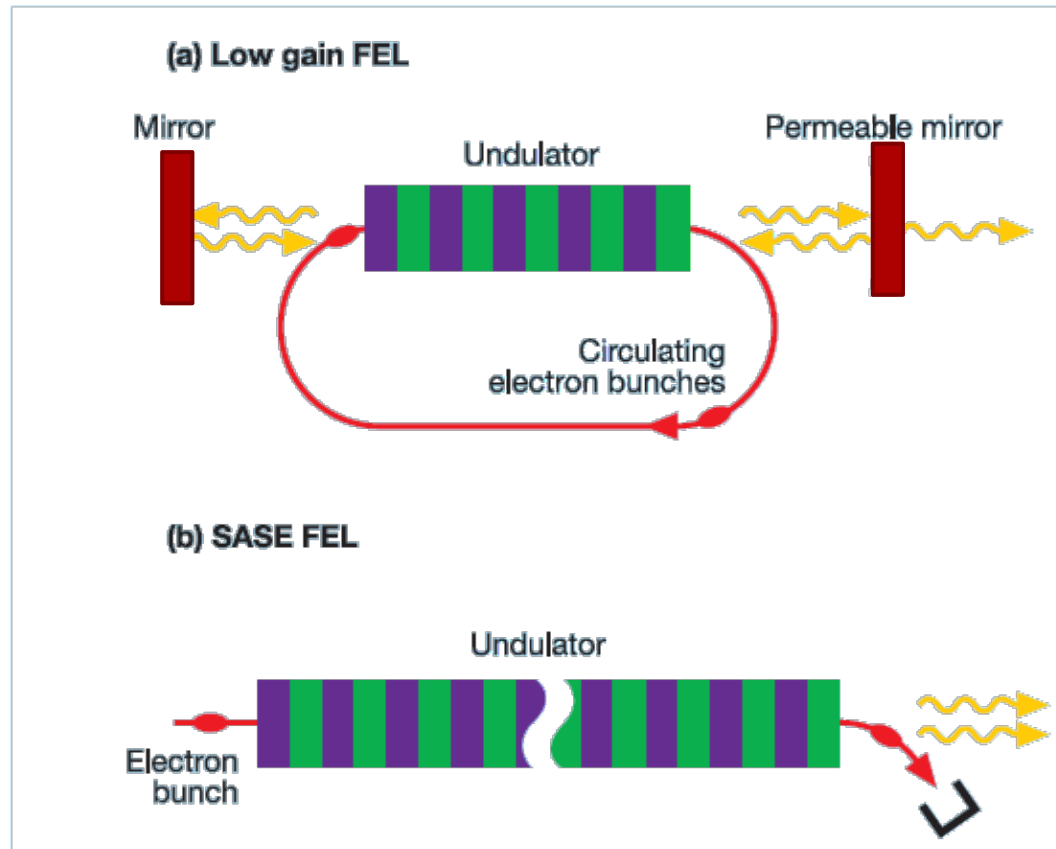
- ▶ Physics of single particle emission in undulator
- ▶ Physics of coupling between single particle and electric field in undulator
- ▶ Physics of collective effects of many particles

Quantum laser



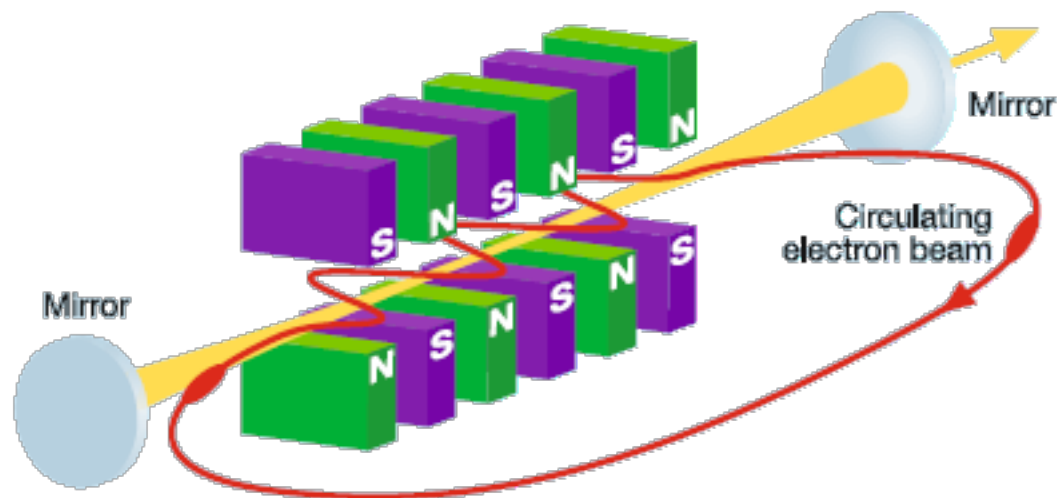
- ▶ quantized energy levels
- ▶ energy pump to create population inversion
- ▶ stimulated emission of radiation

FEL



- ▶ energy source: kinetic energy of beam
- ▶ stimulated emission of radiation
- ▶ optical resonator or SASE

Low gain FEL



- ▶ The bunches make very many passages through the undulator.
- ▶ Upon each passage the light intensity grows by only a few per cent, which is the reason why such a device is called a *low-gain FEL*.
- ▶ However, it does not prevent the FEL from reaching very high output powers (in the order of Gigawatts) if the electron beam makes a sufficiently large number N of passages and if the lifetime of the optical eigenmode is long enough