Introduction to Laser Physics

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High Gradient Wakefield Accelerators

Sesimbra, Portugal, March 2019

Outline

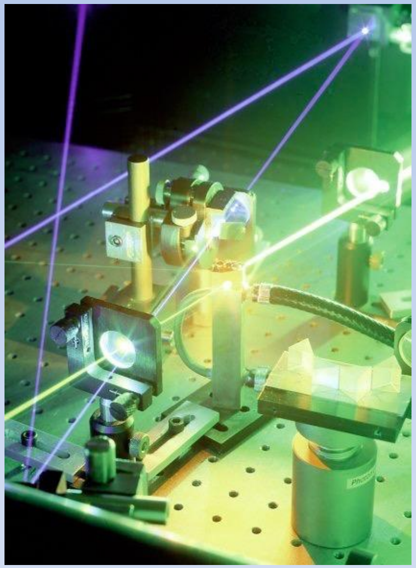
- What is a laser?
- Basic laser physics
- Different types of laser systems.
- High power lasers

Suggested reading:

- ‘Lasers’, A.E. Siegman, University Science Books
- ‘Principles of Lasers’, O. Svelto, Springer
- ‘Laser Physics’, S. Hooker & C. Webb, Oxford University Press
- ‘Optical Electronics in Modern Communications’, A. Yariv, Oxford University Press

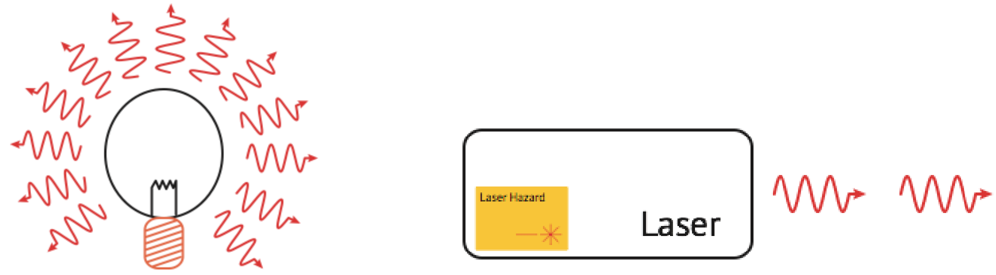
LASER

Light Amplification by Stimulated Emission of Radiation

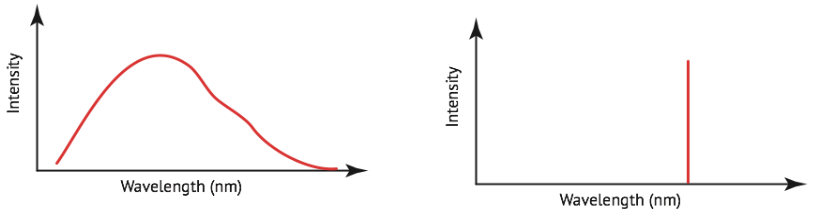


What makes lasers special?

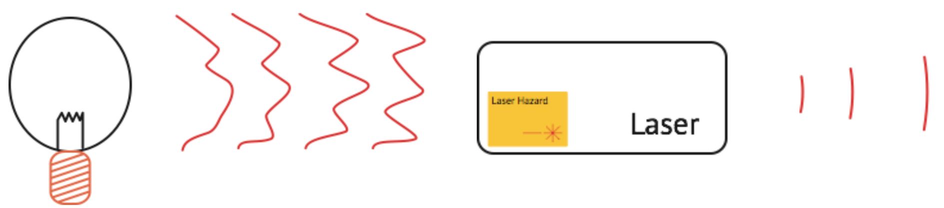
- They produce a directional beam.



- They have a narrow spectrum (or bandwidth).

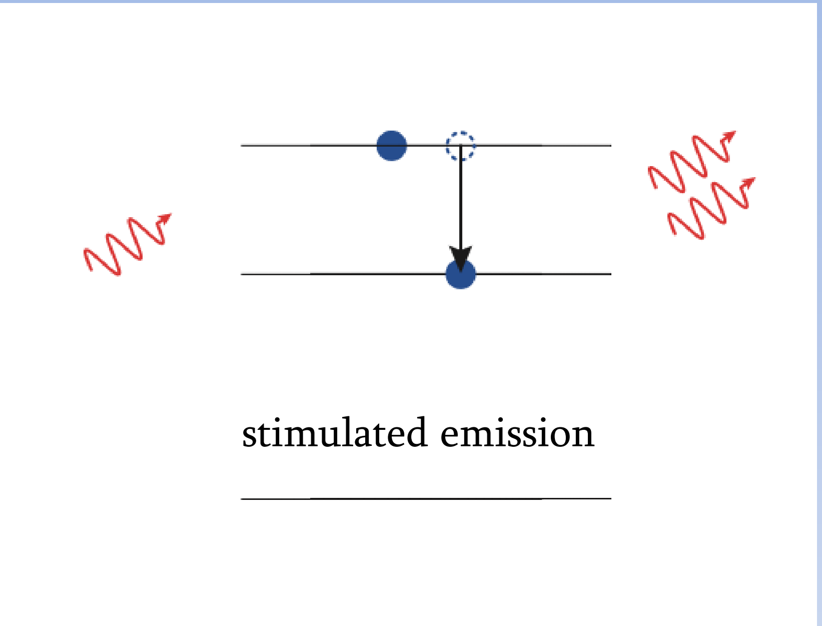


- They are coherent.

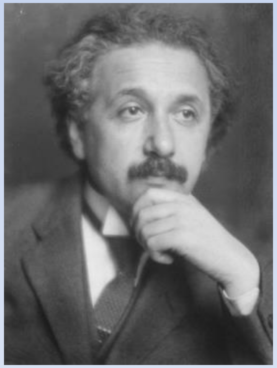


Einstein model

- Einstein identified 3 ways in which atoms exchange energy with a radiation field

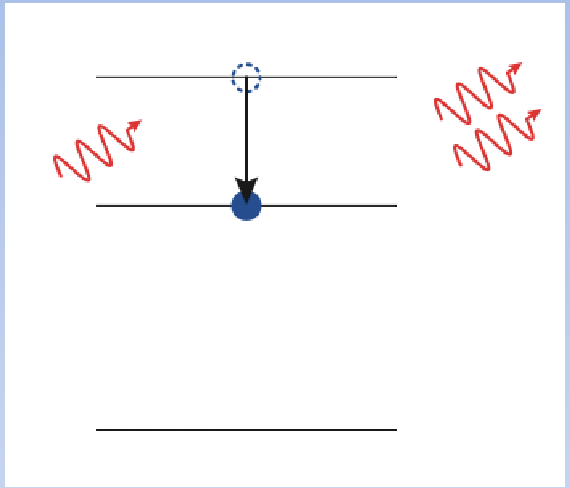


- Absorption
- Spontaneous emission
- Stimulated emission
- Rate of absorption/stimulated emission dependent on no of photons & number of atoms in lower/upper state.
  - *photon needs to have correct energy*
  - *the number of photons can be <u>amplified</u>*

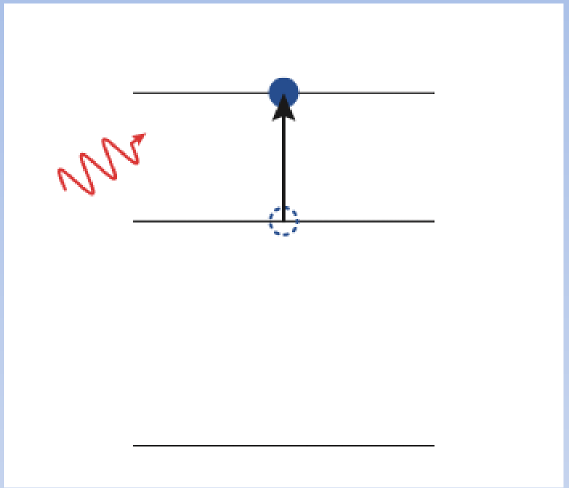


Albert Einstein

Lasers: the basic idea



We want lots of this....



... but not much of this

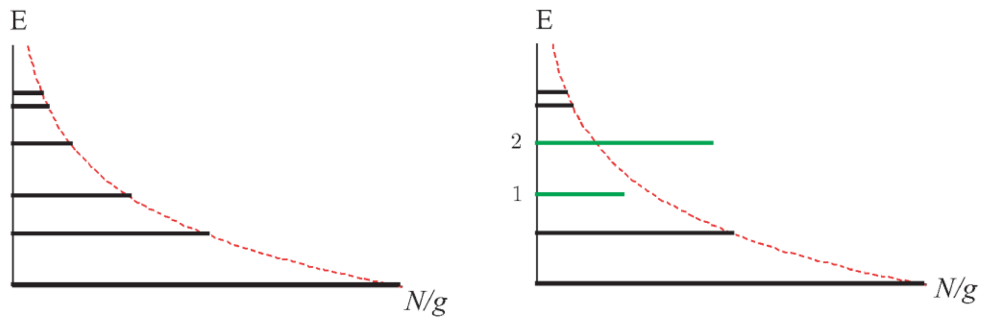
Hence we need a **population inversion,**

i.e. more atoms in the upper level than in the lower level.

Population Inversion

Population inversion

A population inversion is unusual:



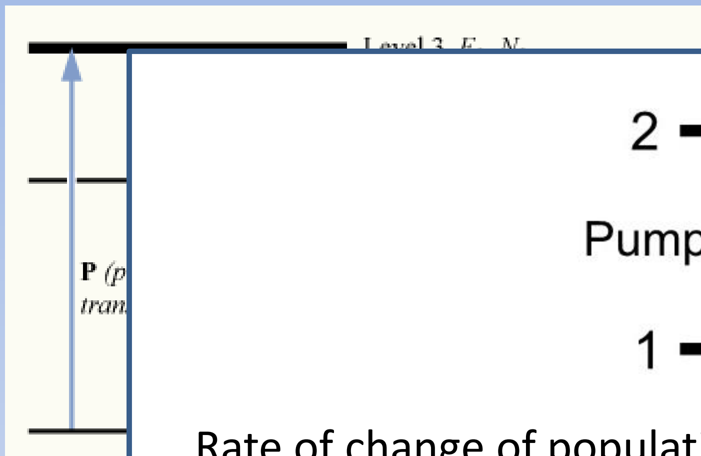
In thermal equilibrium

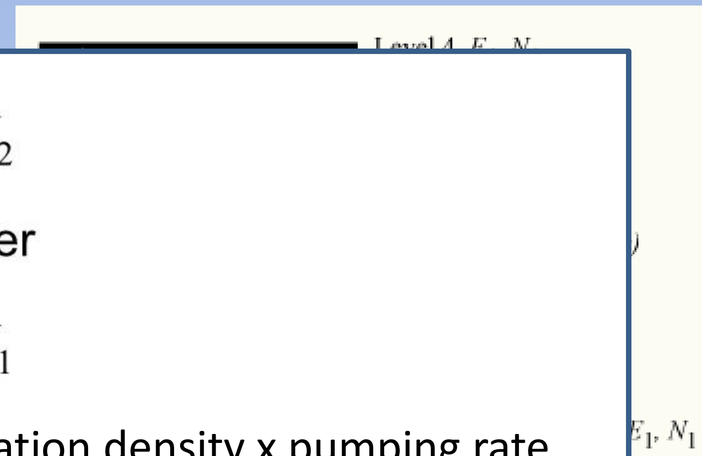
$$\frac{N_2}{N_2} = \frac{g_2}{g_1} \exp\left(-\frac{\Delta E}{kT} \right)$$

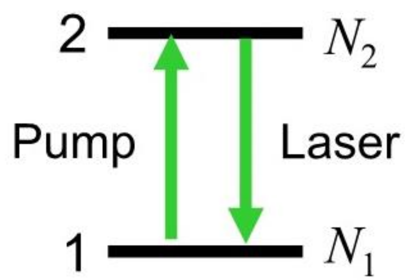
and hence population inversion not possible in this case.

Need to pump (add energy to) the gain medium to get an inversion

3 and 4 level lasers







Rate of change of population ∝ population density x pumping rate

Absorption & stimulated emission equally likely

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

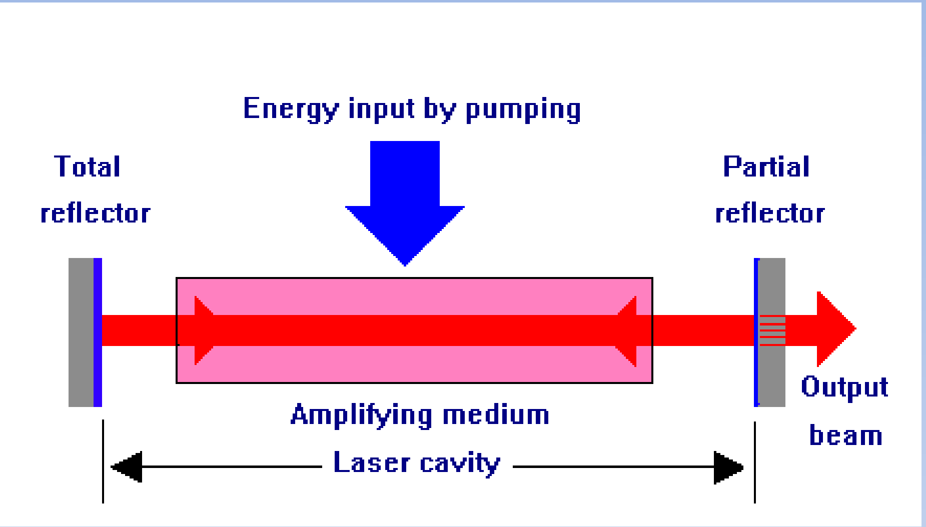
- Ca
- So
- 3 l ... om 1 – 3
- 4 level – N2 = 0, so any population in 3 is an inversion – less pump, more efficient!

- Not necessarily monochromatic:
- Some lasers have broad emission range (although not white light!)

Making a laser

- All laser oscillators (as opposed to amplifiers) have 3 parts:
- **Gain medium** – gas, solid state, liquid – what provides the lasing transition.
- **Pump** – source of energy to create population inversion – usually another light source e.g. flashlamp or another laser, can be electrical discharge or current.
- **Cavity** – need to recirculate photons to stimulate emission on lasing transition – often mirrors around gain medium, can be medium itself.
- Lasing threshold – when gain (no. photons emitted in round trip) exceeds loss (number lost to absorption, through mirrors etc.).
- Do you want laser light all the time (continuous wave, cw) or pulsed? Pulses can be from femtosceonds - nanoseconds
- And that's it!

Cavity



- 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

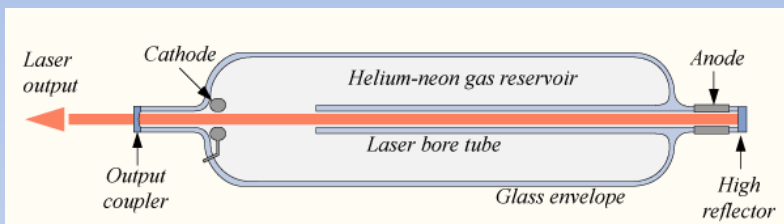
Types of laser

- **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

But you don’t get every colour! Dependent on lasing transition

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!

- CO_2 lasers (10.6mm).
- Industrial & medical applications.
- Research on increasing peak power at BNL.

Liquid lasers

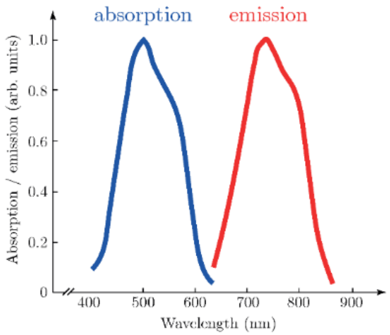
- Less common, usually organic dyes – Rhodamine 6G
- Can get orange/yellow, hard to get with other gain media.
- Often carcinogenic materials.

Solid state lasers

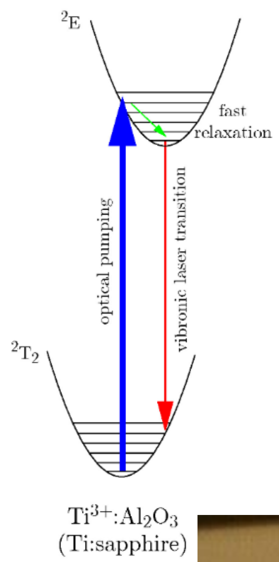
- Most important class of lasers: many lasers have solid gain media:
- ‘solid state’ generally means lasing ions doped into crystalline/glass host
  - e.g. Ti:sapp, Nd:YAG, Nd:glass
- Other solid state lasers referred to separately:
  - Semiconductor diode lasers (often used to pump other lasers)
  - Fibre lasers – usually rare earth ions e.g. Er, Yb, doped into glass.
- Pumping mechanisms:
  - Broadbandwidth white flashlamps (Nd:YAG)
  - Other lasers (Ti:sapp, fibre lasers)
  - Electricity (semiconductor diodes)

Titanium sapphire lasers

Ti:sapphire

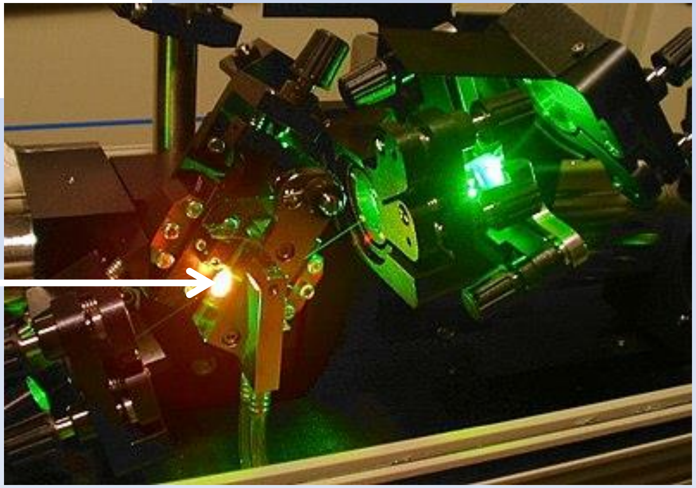


- Simple spectrum: Only single 3d electron
- Four-level laser
- τ_2 = 3.8 μs, $\tau_1 \approx$100ps
- Largest bandwidth of any laser
  - allows generation of pulses as short as 5fs



- Hugely important laser
- Bandwidth! – 300nm
- Shortest pulses.
- Absorbs at 500nm – pump with green laser.
- Commercially available petawatt (PW) Ti:sapp lasers
- Workhorse of science research

Ti:sapp crystal

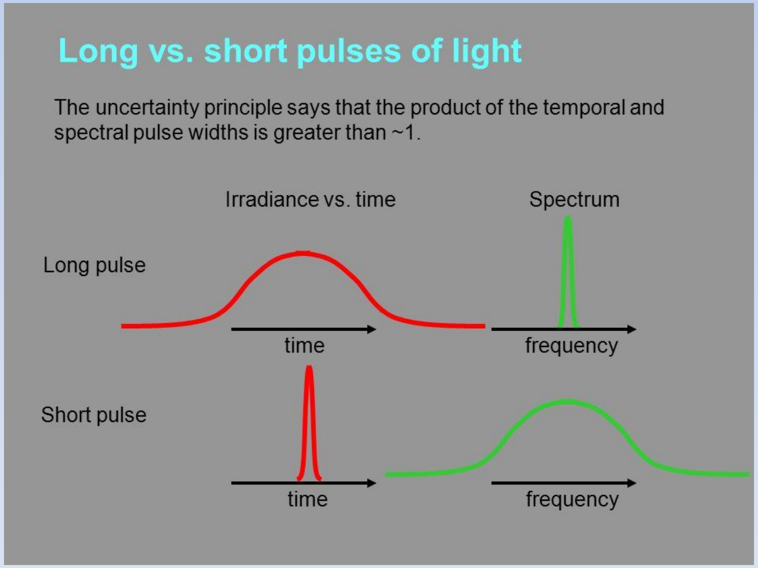


High power lasers

- 100s TW & PW lasers - laser plasma wakefield acceleration, laser ion acceleration
- Usually Ti:sapp (fs), sometimes Nd doped systems

- How do you make a PW laser without damaging it?
- Chirped Pulse Amplification (CPA). (Also useful for winning Nobel prizes).

- But need to know something about ultrashort pulses to know how this works.

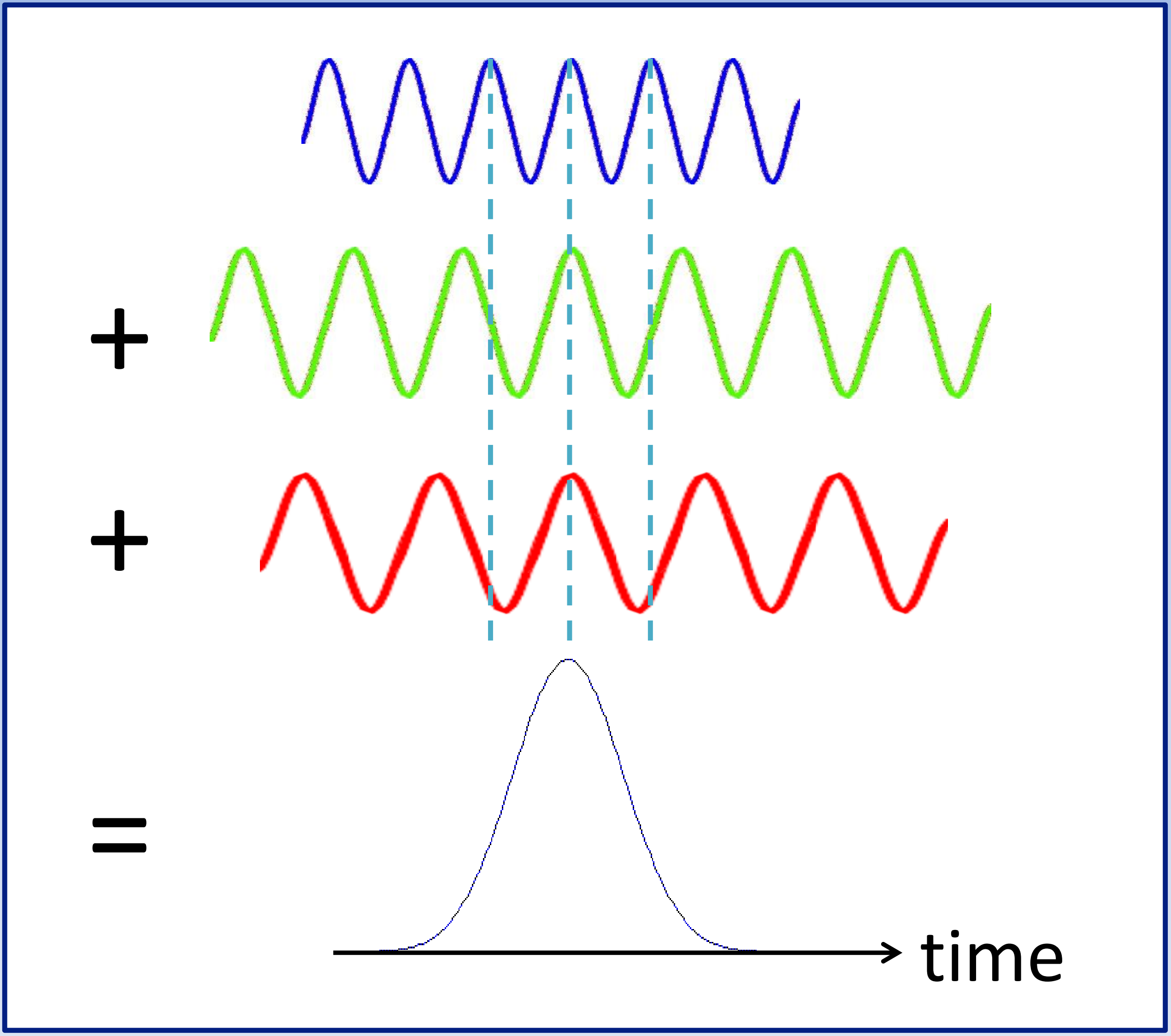


- Fourier synthesis of short pulse requires many frequency components - spectrum!

- When all components have no phase difference pulse is shortest it can be for a given spectrum.

- Pulse is Fourier transform limited (FTL).

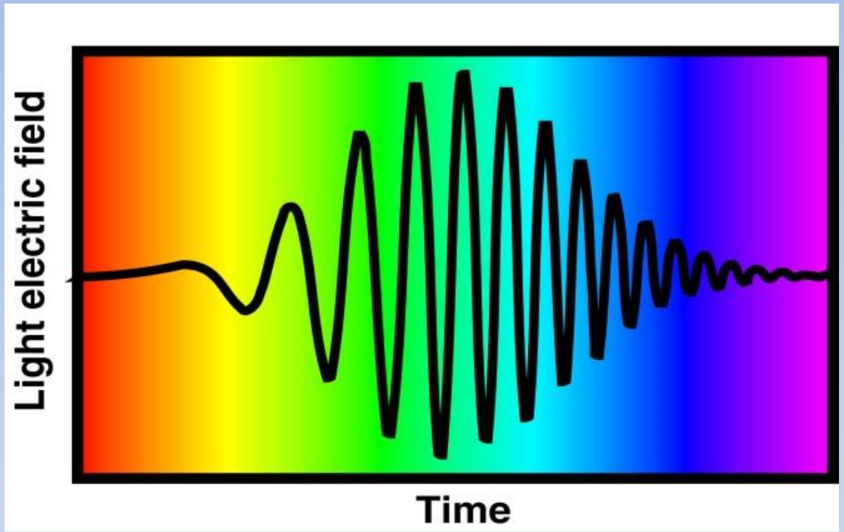
Fourier synthesis of a short pulse

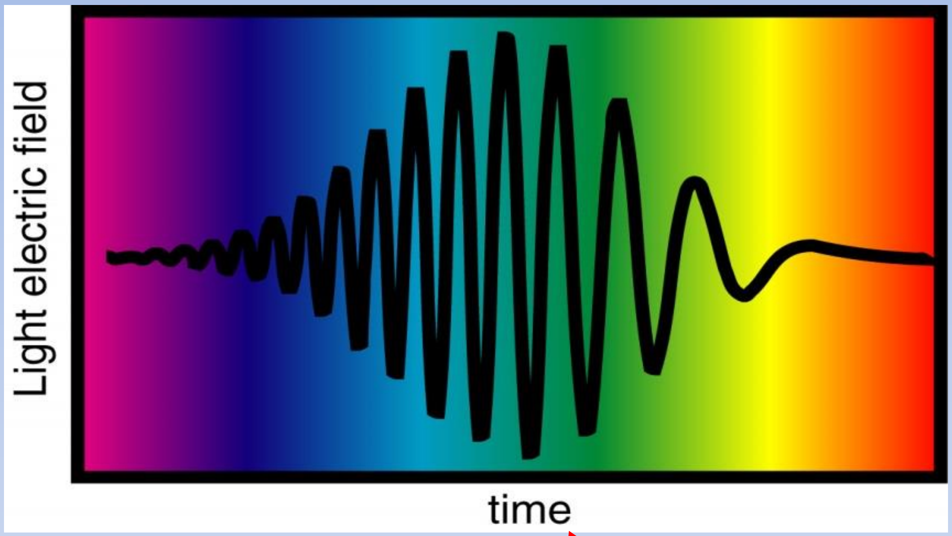


'flat phase'

Chirped pulses

Chirp of an optical pulse is the time dependence of its instantaneous frequency





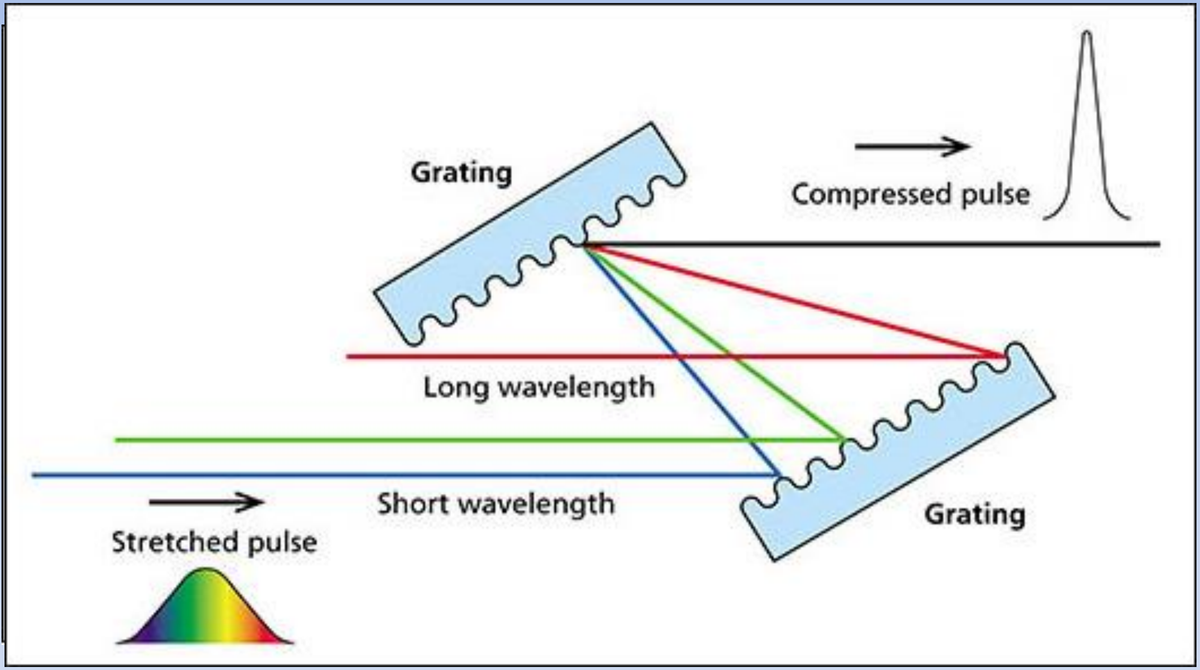
Frequency increases with time - Positive chirp

Frequency decreases with time - Negative chirp

Both pulses longer in time than if not chirped – flat phase, FTL

How to chirp a pulse

$$d(\sin\theta + \sin\alpha) = m\lambda$$

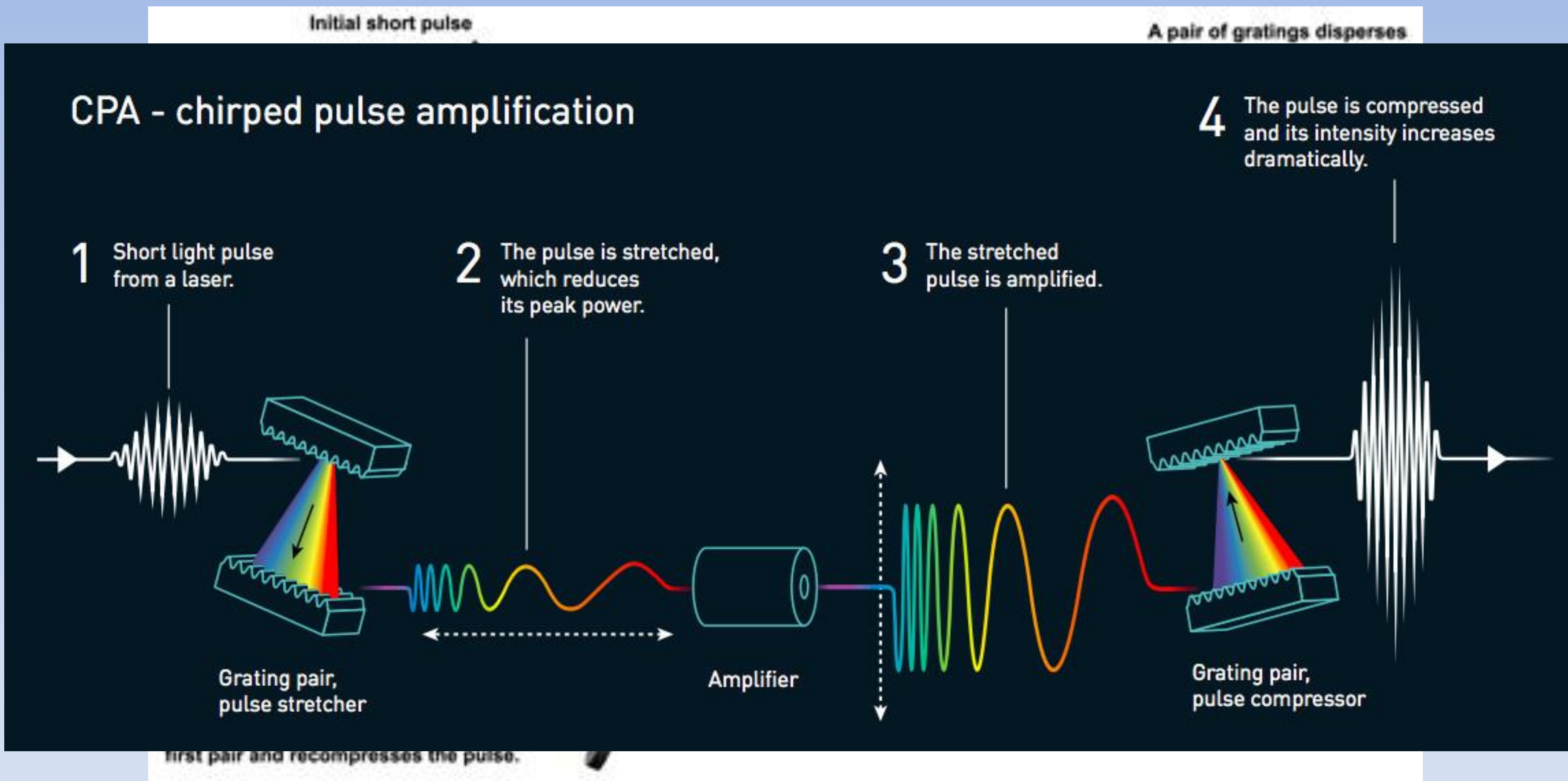


Grating compressor

Red light→ longer distance → closer to blue

Blue light → shorter distance → catches up

Chirped Pulse Amplification



Short pulse → Stretch in time (chirp) → Amplify → Compress in time

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CPA works!

The Cockcroft Institute of Accelerator Science and Technology

Tweets Tweets & replies Media

Thales Science @ThalesScience · Mar 8

[#Laser] World record breaking News!!! 10.9PW, 327J at 1 shot/min compressed in a pulse just 22.3 femtoseconds long, the World highest power achieved with the Thales laser system @ELINPMagurele in Romania! #LaserTechnologies #ThalesLaserTeam

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High power lasers – further research

- **CPA hugely successful – operational 10 PW laser!**

10,000,000,000,000,000 W

So what's the problem? Is laser research over?

- Expensive
- Low repetition rate – 1 shot/hr, /min, /s – still too slow
- So low *average* power
  - e.g. BELLA laser at LBNL
  - Peak power ~ 40J/40fs = 1PW
  - Average power 40J/s = 40W
- Efficiency
  - BELLA uses 130kW electrical power
  - 0.03% wall plug efficiency

For PP research:

32J laser/15kHz = 480kW
@0.03%: **1.6GW**

C. Schroeder et al.
PRST AB 13 101301 (2010)

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Accelerator Laser Research

The Cockcroft Institute of Accelerator Science and Technology

1 White Paper of the ICFA-ICUIL Joint Task Force – High Power Laser Technology for Accelerators

Wim Leemans, LBNL
Chair of the ICFA-ICUIL Joint Task Force and Editor of the White Paper
Mail to: wpleemans@lbl.gov

Executive Summary

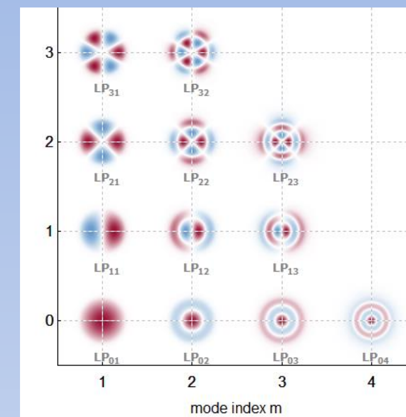
Particle accelerators and lasers have made fundamental contributions to science and society, and are poised to continue making great strides in the 21st century. Lasers are essential to modern high performance accelerator facilities that support fundamental science and applications, and to the development of advanced accelerators. In accelerator and radiation science, which aims at developing advanced acceleration and radiation source concepts, lasers provide the power for laser plasma accelerators or dielectric-structure-based direct-laser accelerators. For present-day light sources they are used to drive photocathodes in high-brightness electron guns; to control and measure beam properties; and to seed the amplification process in the latest generation of light sources that rely on electron-beam-based free-electron lasers. (At the user beamlines of light sources, they are also widely used in pump-probe experiments.) Lasers are also used in radiation sources, such as those producing high harmonics in gases, or those producing intense gamma-ray beams via inverse Compton or Thomson scattering against relativistic electron beams. Medical applications are emerging that rely on laser produced particle and radiation beams that offer the potential to be compact and cost effective.

- LWFA
- Compton scattering
- Ion acceleration
- Photocathodes
- FEL seeding
- Positron generation

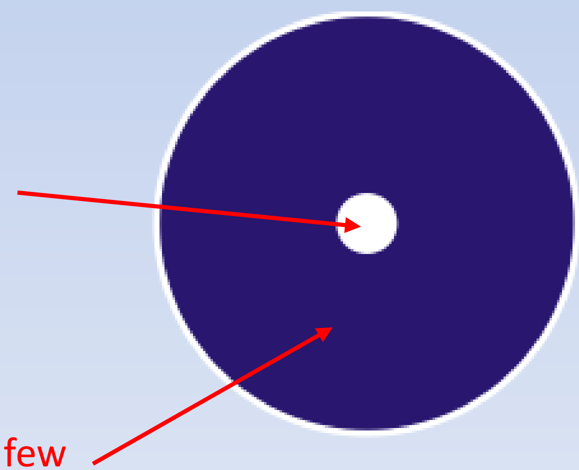
https://www-bd.fnal.gov/icfabd/WhitePaper_final.pdf

One approach - Fibre lasers

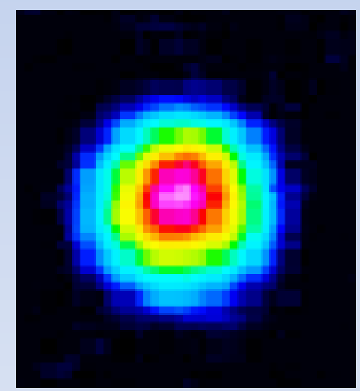
- Optical waveguides
- Light guided and amplified in core doped with lasing ions
- Er ~ 1.5μm, Yb ~ 1μm
- **Efficient - up to 40% wall plug efficiency**
- **High average power – 10s – 100s kW**
- Excellent single mode quality
- Low pulse energy – mJ
- Long(ish) pulses – 100s fs



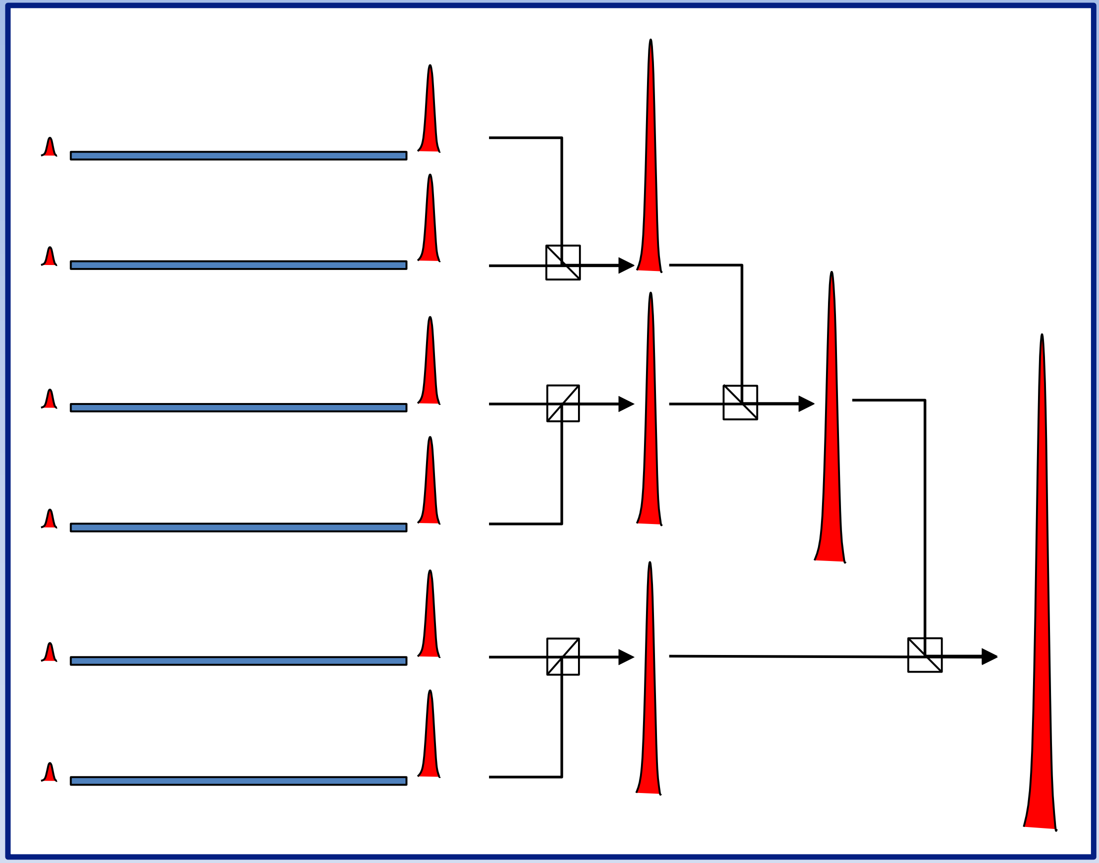
Core – ion doped,
~ few μm diameter



Cladding – few
100 μm diameter

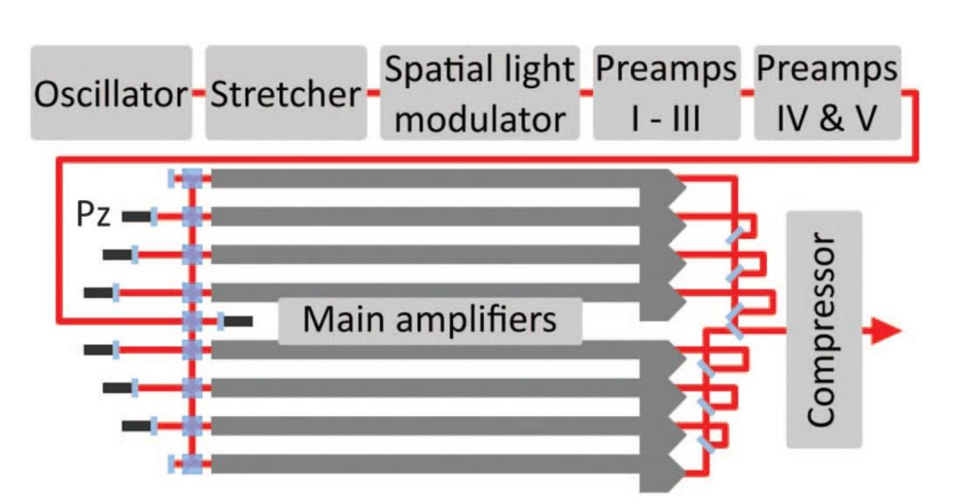


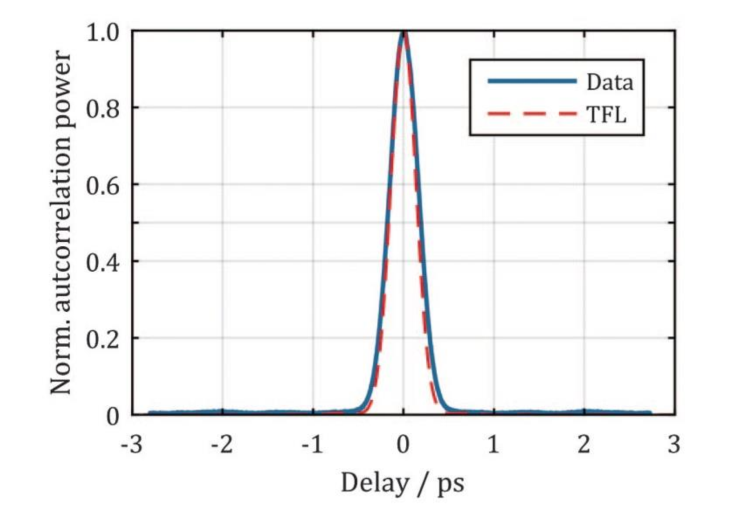
Combine many lasers



Take many efficient, high average, low peak power fibre lasers and add them together
HAPPI lasers – High Average and Peak Power Intense lasers (TM Gérard Mourou)

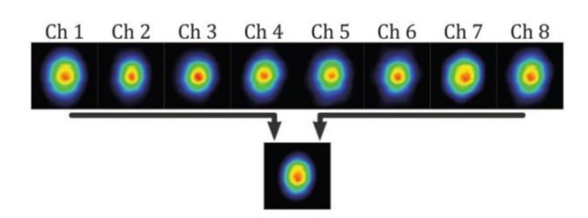
Combination results





Müller et al.,
Opt. Letts. 41, 3439 (2016)

- Seed split and amplified in 8 large fibre amplifiers
- 1 MHz, 1.1 mJ, 260fs
- **1kW average power**



Kienel et al.,
Opt. Letts. 41, 3343 (2016)

- 8 channels combined - spatial & temporal division
- 12mJ, 56kHz, 260fs
- **46GW peak power**

Conclusion