ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lasers: technologies and setups

Stephen Gibson

John Adams Institute for Accelerator Science

Royal Holloway, University of London, UK

Beam Instrumentation
Tuusula, Finland
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Lasers: talk overview

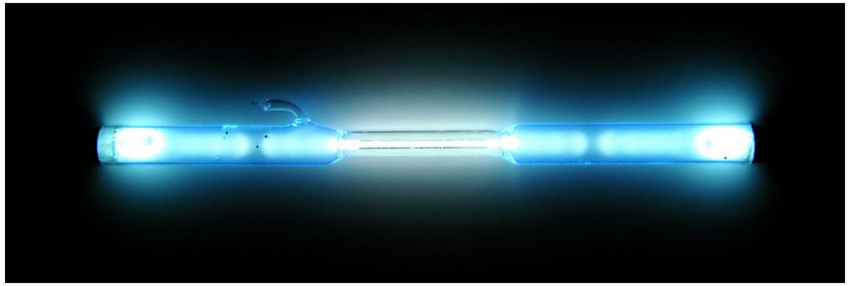
Royal Holloway University of London

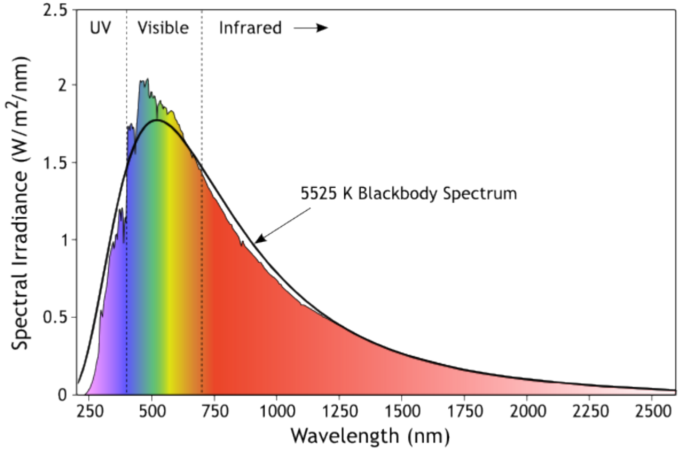
Outline

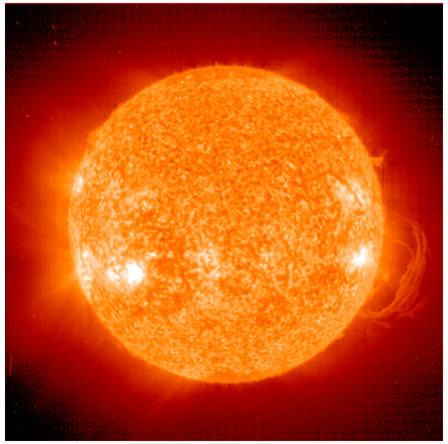
- ***Lasers:*** fundamental principles
- ***Laser types, key parameters***
  - Cavity modes & linewidth
  - Q-switched / mode-locking
  - Chirp Pulse Amplification
- ***Technologies: focus on fibres***
  - Fibre lasers, amplifiers, splitters, switches
  - Optical transmission, EO-modulators
- ***Technology setups***
  - FSI system example

Light sources

- Conventional sources typically emit ***incoherent*** light of ***multiple frequencies***, **in all directions.**
- Not so useful for beam instrumentation…







‘An elegant weapon for a more civilised age…’

…not a ‘laser sword’

Laser fundamentals

Laser light properties:

- In 1958 Arthur Schawlow and Charles Townes laid down the theoretical framework for an "Optical Maser"
- Now known as the laser:

Light
Amplification by
Stimulated
Emission of
Radiation

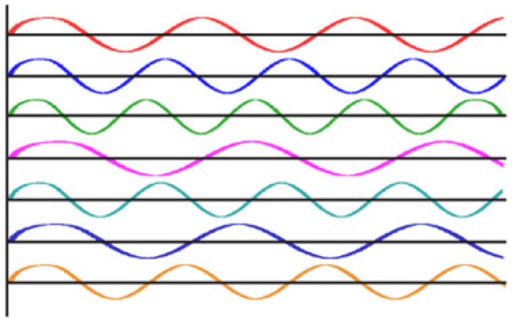
Essential properties of laser light:

*Monochromatic**

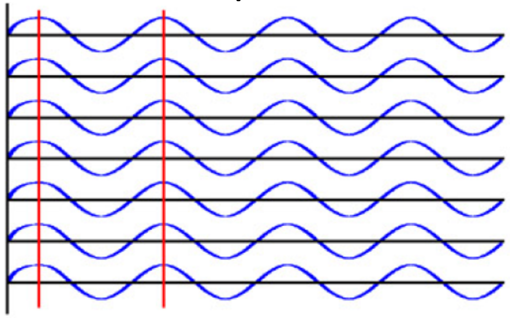
Coherent

Highly Directional

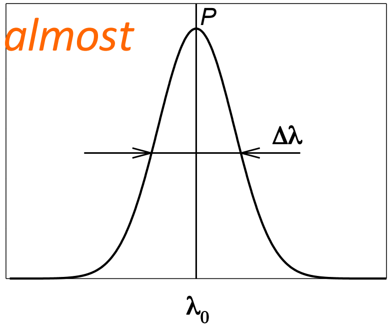
Incoherent light waves:
- difference frequencies
- different phases



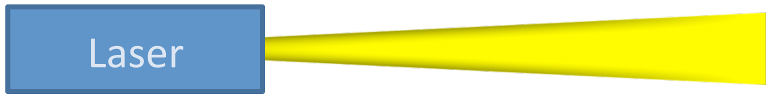
Coherent light waves:
- same frequency
- same phase



* almost



Extremely useful for precision measurements



Angular divergence

$$\theta = M^2 \frac{\lambda_0}{\pi W_0}$$

M^2 **- Laser quality factor**

W_0 **- beam radius in the beam waist**

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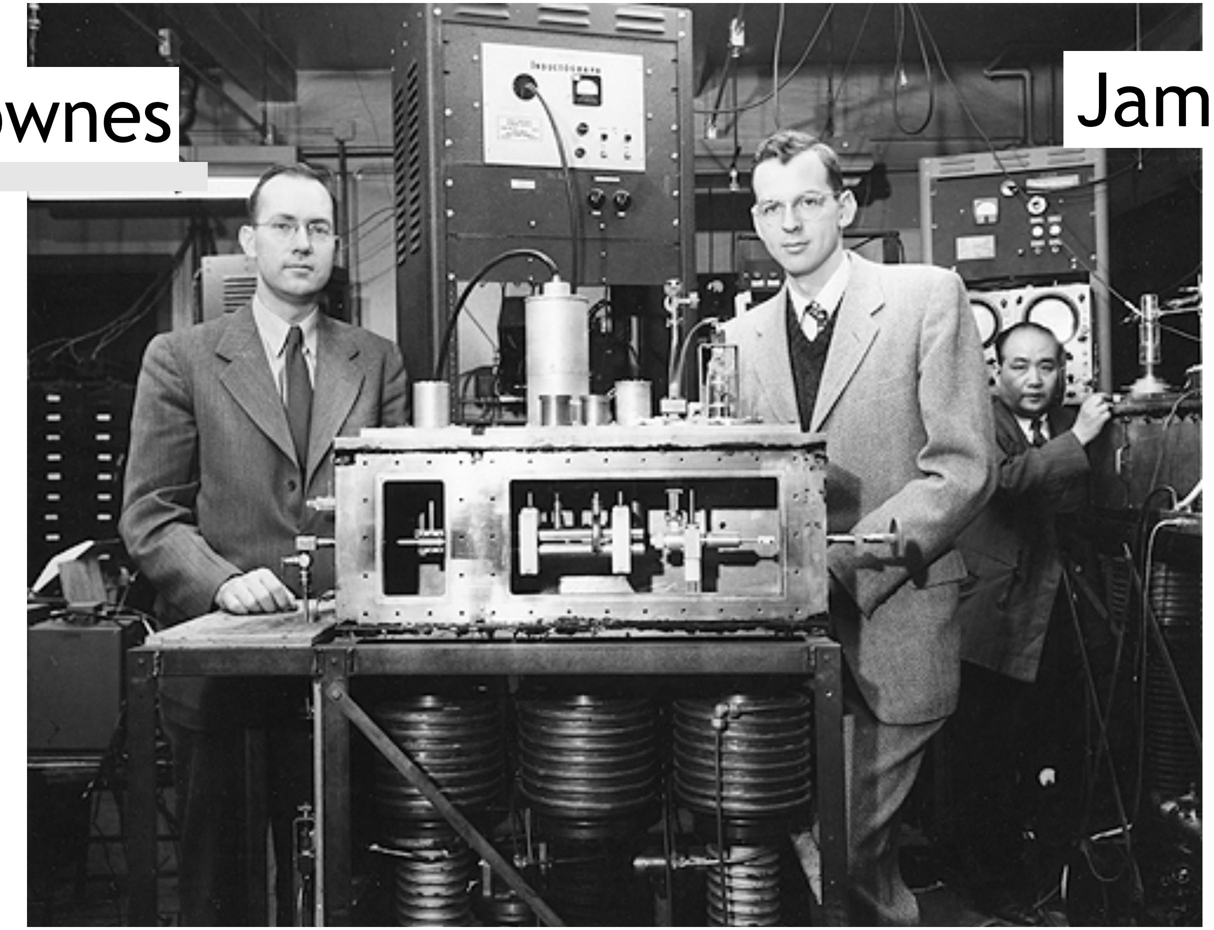
Maser came first, 1955:

Microwave Amplification by Stimulated Emission of Radiation

Charles Townes

James Gordon



Credit: Bettmann/Corbis

Columbia University

Independently invented at: Lebedev Labs, Moscow,

Charles Townes

Nicolay Basov

Aleksandr Prokhorov

Physics 1964

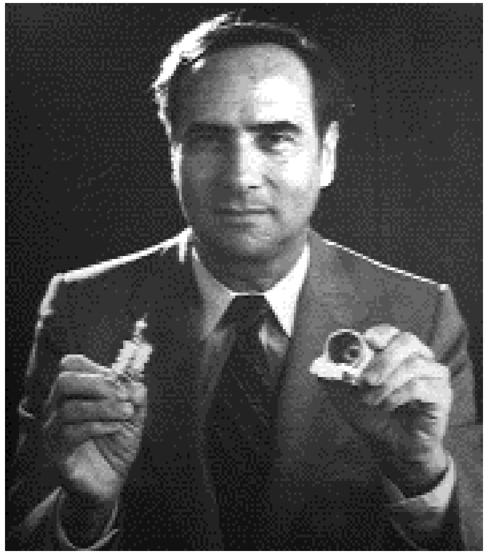
"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser–laser principle"

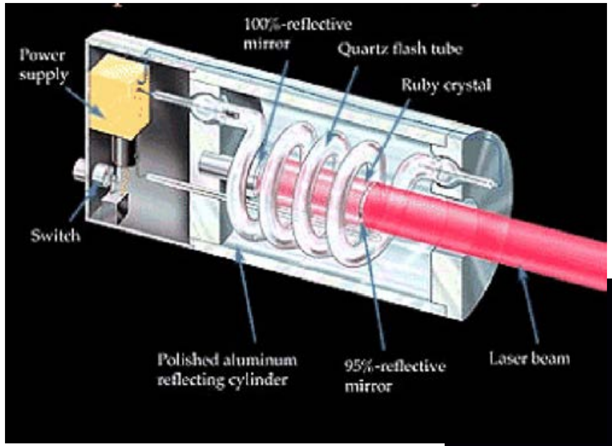
Intro to lasers, Lui Roso 1st LA3net school

Then the first laser, 1960:

Light Amplification by Stimulated Emission of Radiation

T H Maiman ***Ruby laser*** @ 694 nanometers





First laser was named as first optical maser

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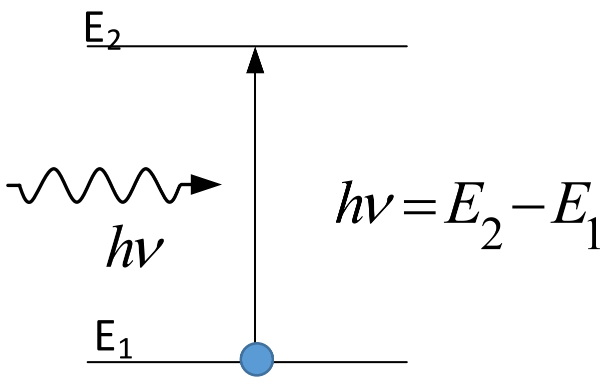
Laser fundamentals: atomic transitions

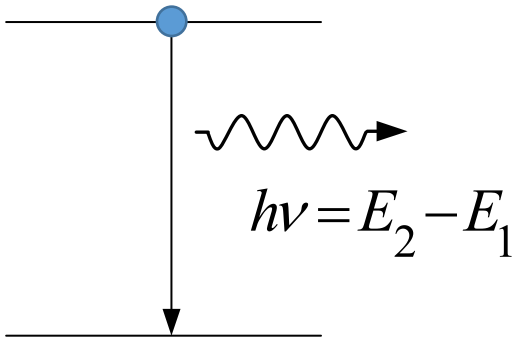
- Transitions of electrons between atomic energy levels fall into three categories:

Photon absorption



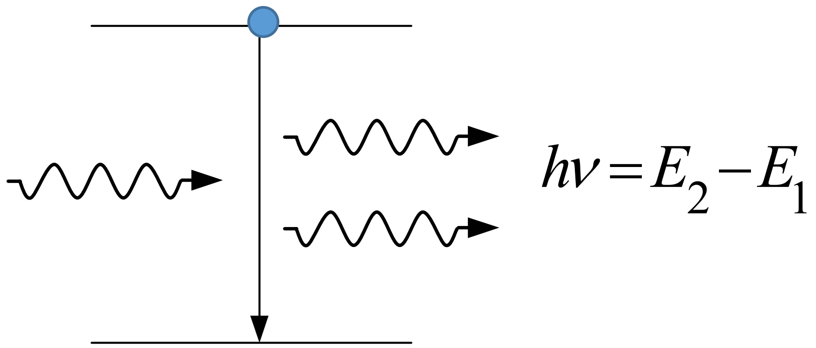
Photon energy transferred to atomic electron, which transitions to a higher energy level, so the atom Is excited.

Spontaneous emission



Natural de-excitation to the lower energy level, emitting a photon

Stimulated emission

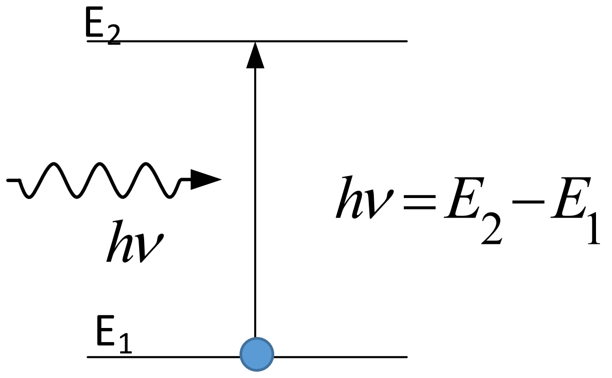


A photon of correct energy perturbs the excited state creating an identical, duplicate photon from the de-excitation.

Laser fundamentals: atomic transitions

- Transitions of electrons between atomic energy levels fall into three categories:

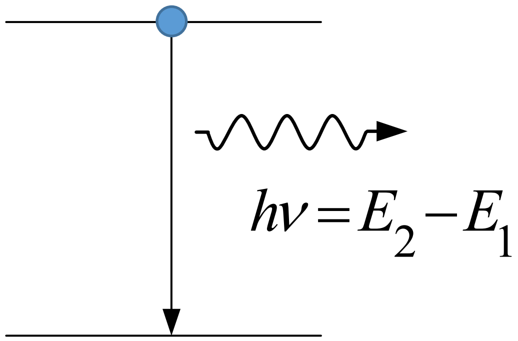
Photon absorption



Rate depends on the number of atoms in the ***lower*** energy level and incident photon flux, F and absorption cross section, σ_{12}.

$$\frac{dN_1}{dt} = -\sigma_{12} F N_1 = -B_{12} N_1 u_\nu$$

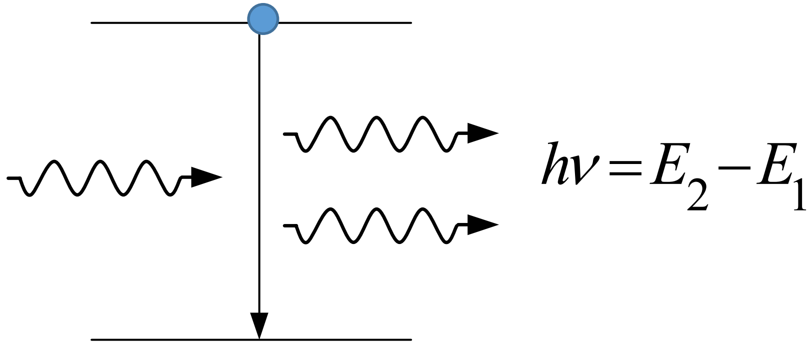
Spontaneous emission



Rate depends on the number of atoms in the ***higher*** energy level and lifetime, τ_{SP}

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau_{SP}} = -A_{21} N_2$$

Stimulated emission



Rate depends on the number of atoms in the ***higher*** energy level photon flux, F and stimulated emission cross section, σ_{12}.

$$\frac{dN_2}{dt} = -\sigma_{21} F N_2 = -B_{21} N_2 u_\nu$$

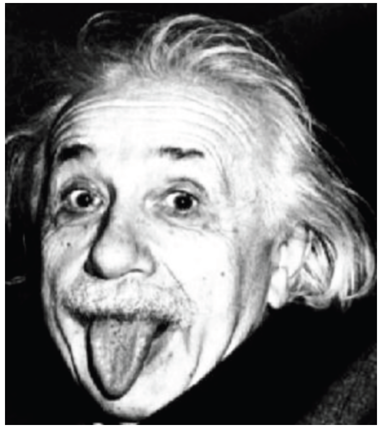
The proportionality constants are the Einstein A and B coefficients.

U_ν is the energy density of radiation

Laser fundamentals: Einstein coefficients

- When in equilibrium: $B_{12} N_1 u_\nu = A_{21} N_2 + B_{21} N_2 u_\nu$

Photon absorption *Spontaneous emission* *Stimulated emission*

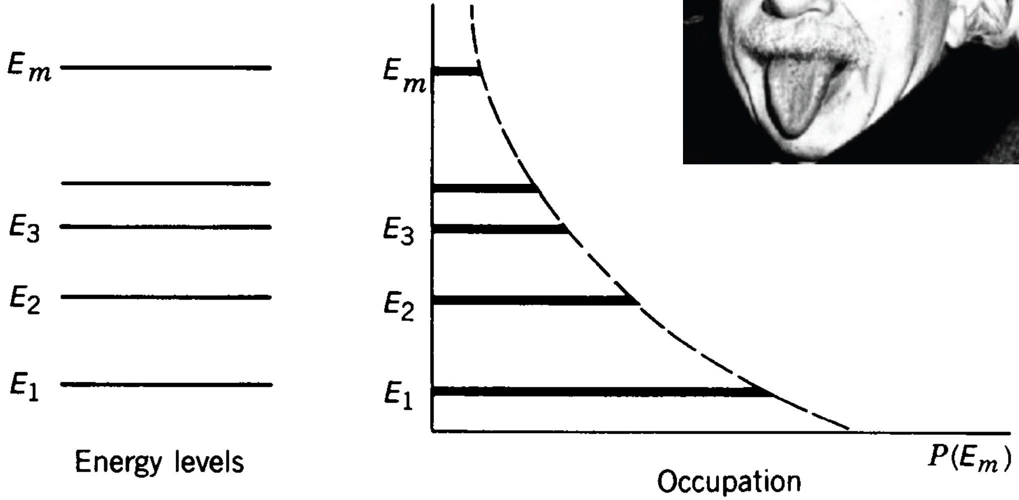


- Solve for the energy density:

$$u_\nu = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

Using Boltzmann:

$$u_\nu = \frac{A_{21}}{B_{21}} \frac{1}{(B_{21}/B_{21}) e^{h\nu/kT} - 1}$$



Boltzmann distribution gives probability that energy E_m in an arbitrary atom is occupied. When in thermal equilibrium, the relative population of levels is:

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{k_B T}\right)$$

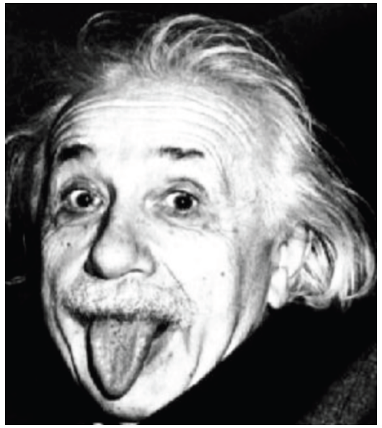
To agree with Planck's radiation formula, Einstein showed:

$$B_{12} = B_{21}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}$$

If $E_2 > E_1$ then $N_2 < N_1$

Laser fundamentals: Einstein coefficients



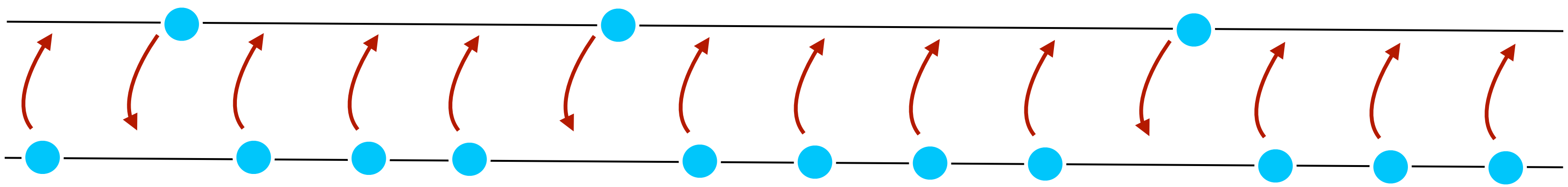
- Thus for atoms in thermal equilibrium, the ratio of stimulated emission rate to spontaneous emission rate is:

$$\frac{stimulated\ emission}{spontaneous\ emission} = \frac{B_{21}u_\nu}{A_{21}} = \frac{1}{e^{h\nu/kT} - 1}$$

- Essentially, the *rate of induced emission is extremely small for normal temperatures*
- Normal light sources are dominated by spontaneous emission, giving ***incoherent light***
- To create laser action by stimulated emission, we need to place more electrons in the upper energy level. This is known as ***population inversion*** *and is achieved by* ***Optical Pumping***

Laser fundamentals

Population inversion by optical pumping

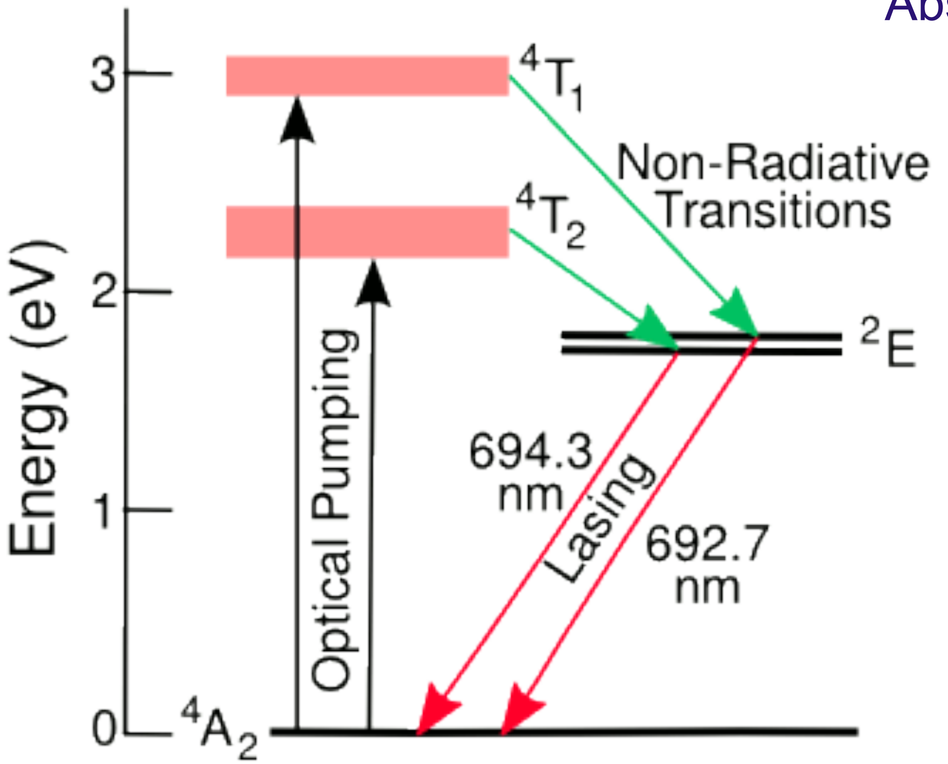


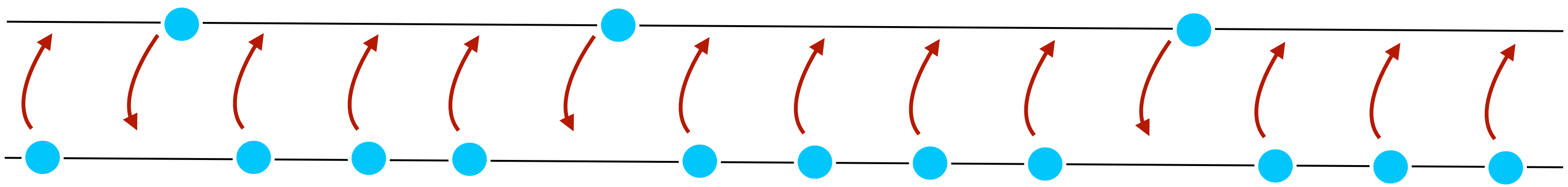
Normally, more electrons in the ground state than in the excited state
Absorption dominates over stimulated emission ... no lasing

Laser fundamentals: population inversion

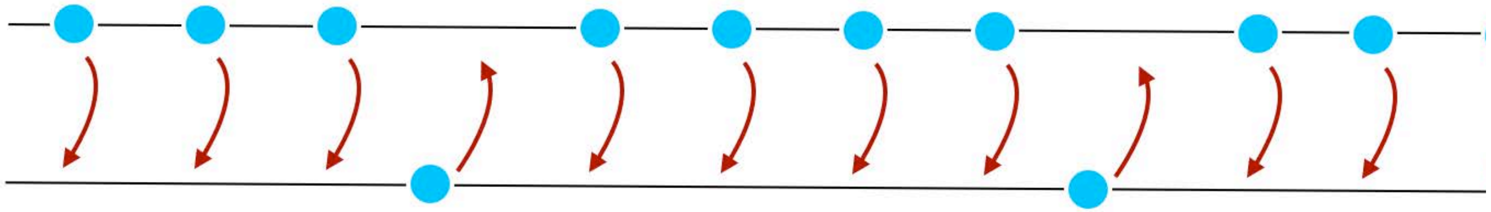
Population inversion by optical pumping

Ruby laser, Chromium-ion, Cr^{+++}





Normally, more electrons in the ground state than in the excited state
Absorption dominates over stimulated emission ... no lasing



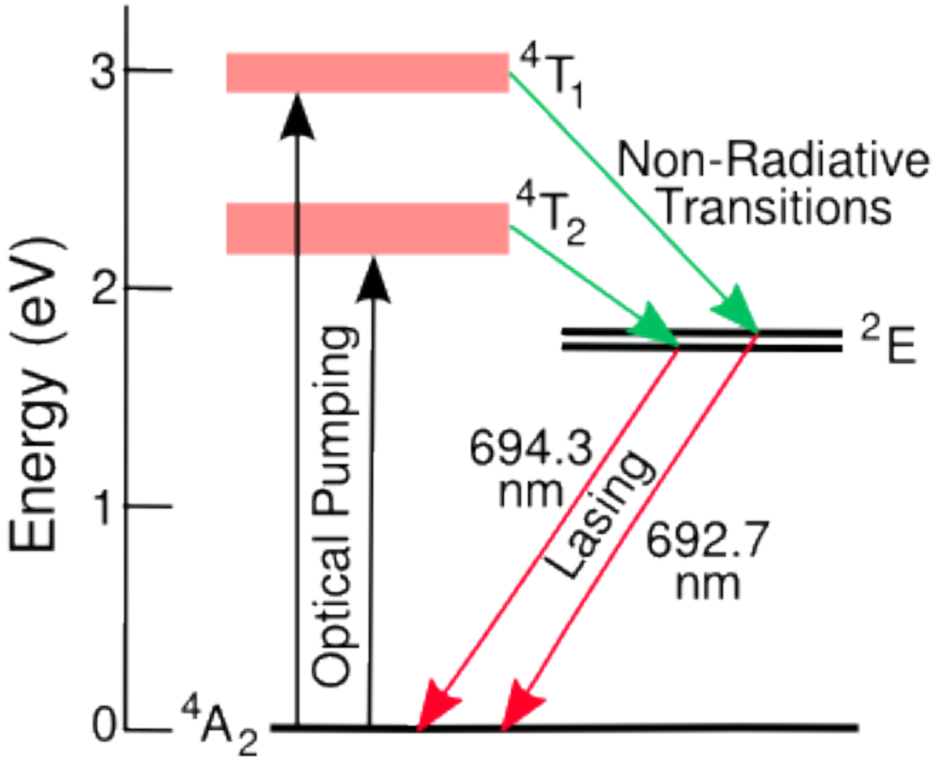
If, more electrons in the excited state than in the ground state then stimulated emission dominates over absorption ... lasing !!!

Intro to lasers, Lui Roso 1st LA^{3}net school

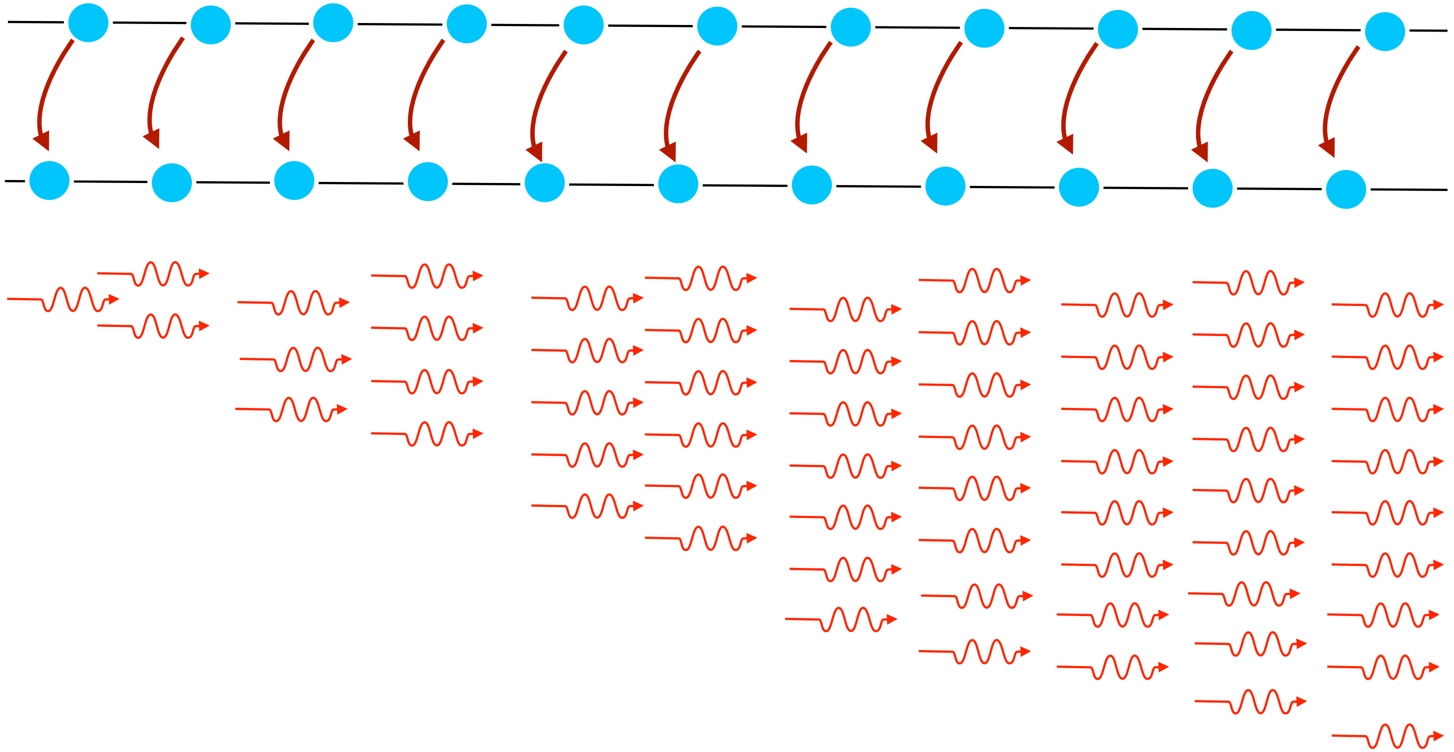
Laser fundamentals: chain reaction

Population inversion by optical pumping

Ruby laser, Chromium-ion, Cr^{+++}



Chain reaction: *Stimulated Emission -> Light Amplification*



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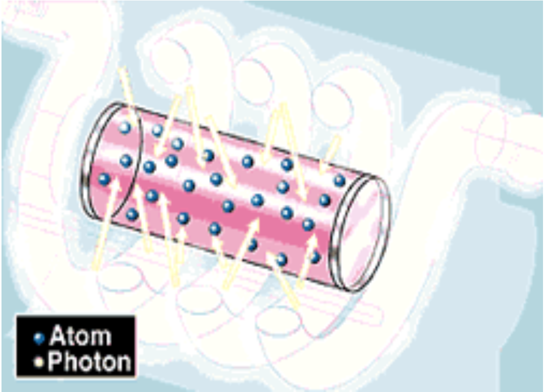
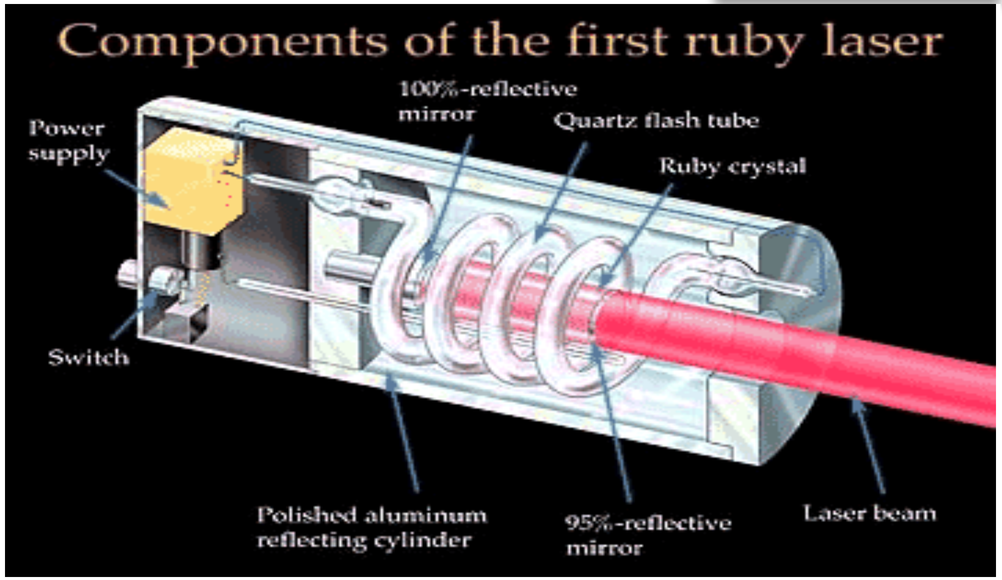
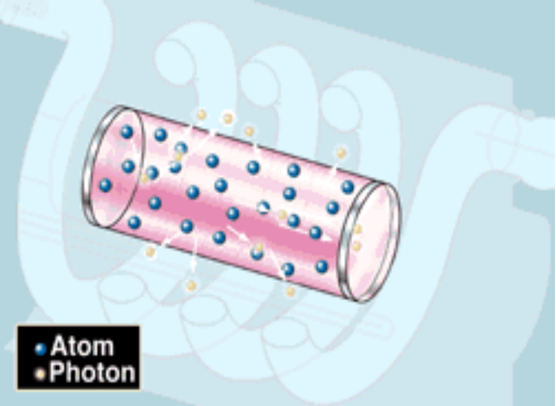
Laser components

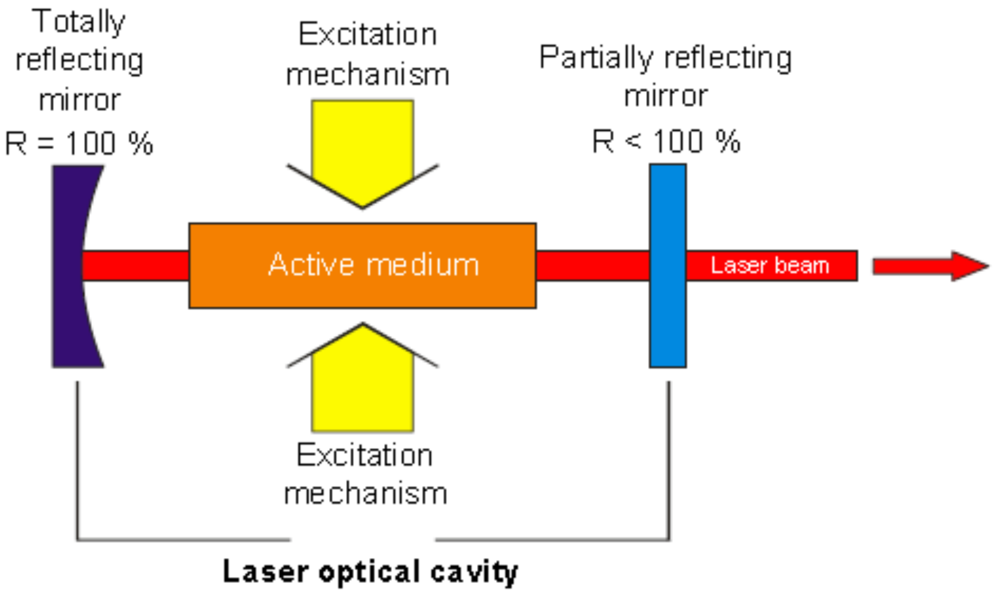
1. High-voltage electricity causes the quartz flash tube to emit an intense burst of light, exciting some of Cr^{3+} in the ruby crystal to higher energy levels.





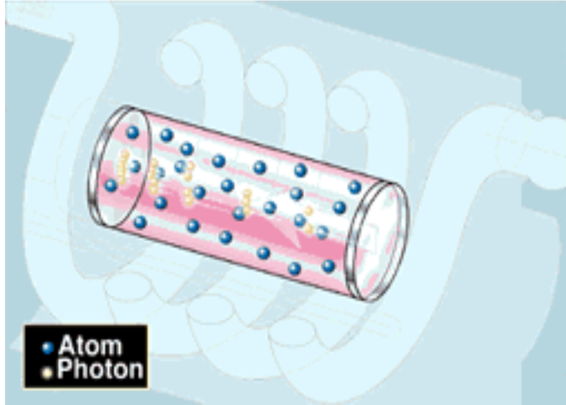
2. At a specific energy level, some Cr^{3+} emit photons. At first the photons are emitted in all directions. Photons from one Cr^{3+} stimulate emission of photons from other Cr^{3+} and the light intensity is rapidly amplified.

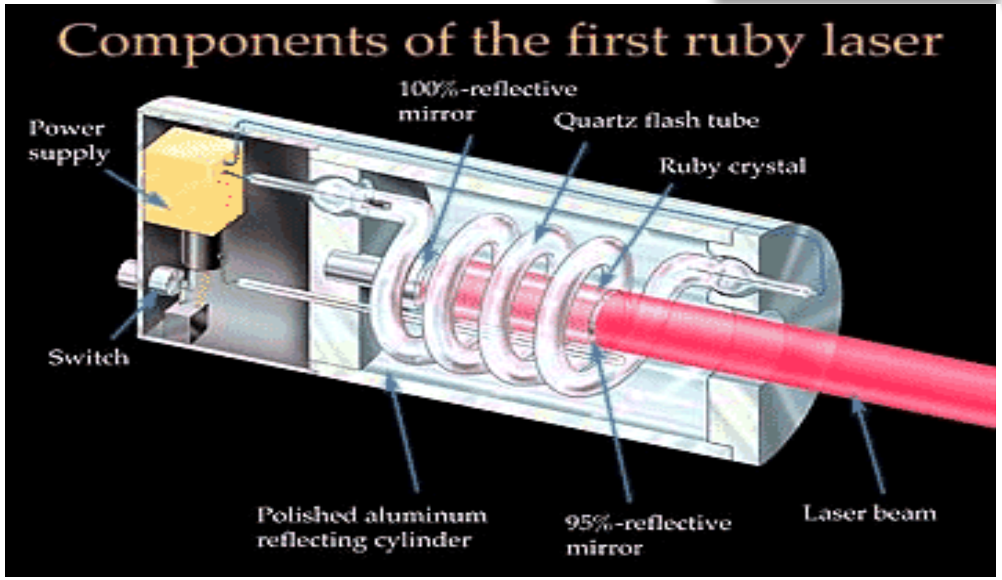




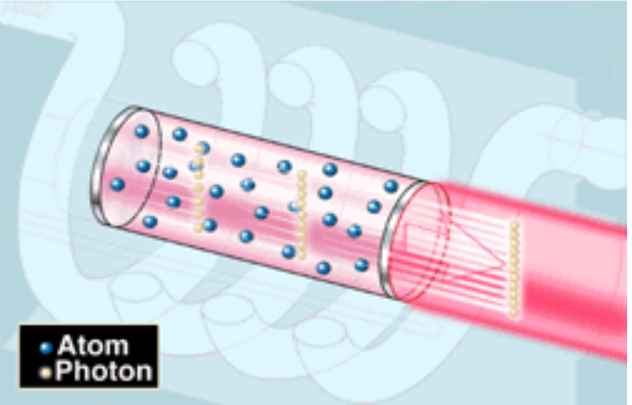
Laser components

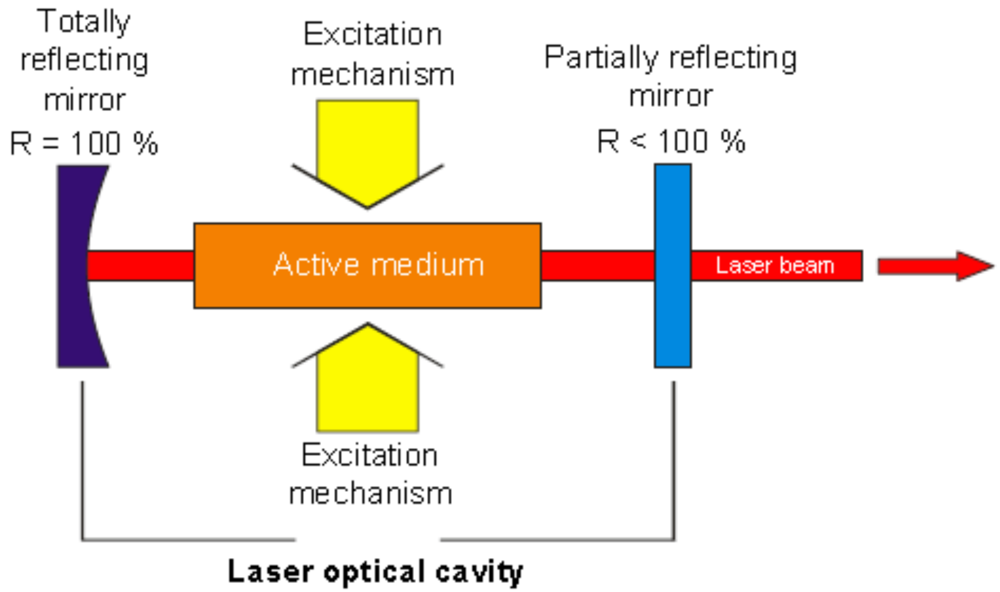
3. Mirrors at each end reflect the photons back and forth, continuing this process of stimulated emission and amplification.





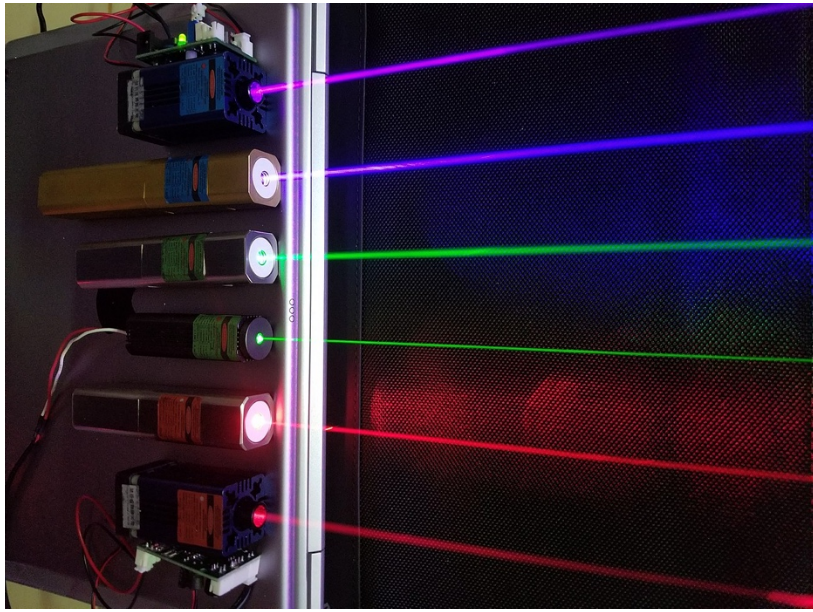
4. The photons leave through the partially silvered mirror at one end. This is laser light.





Laser types and key parameters

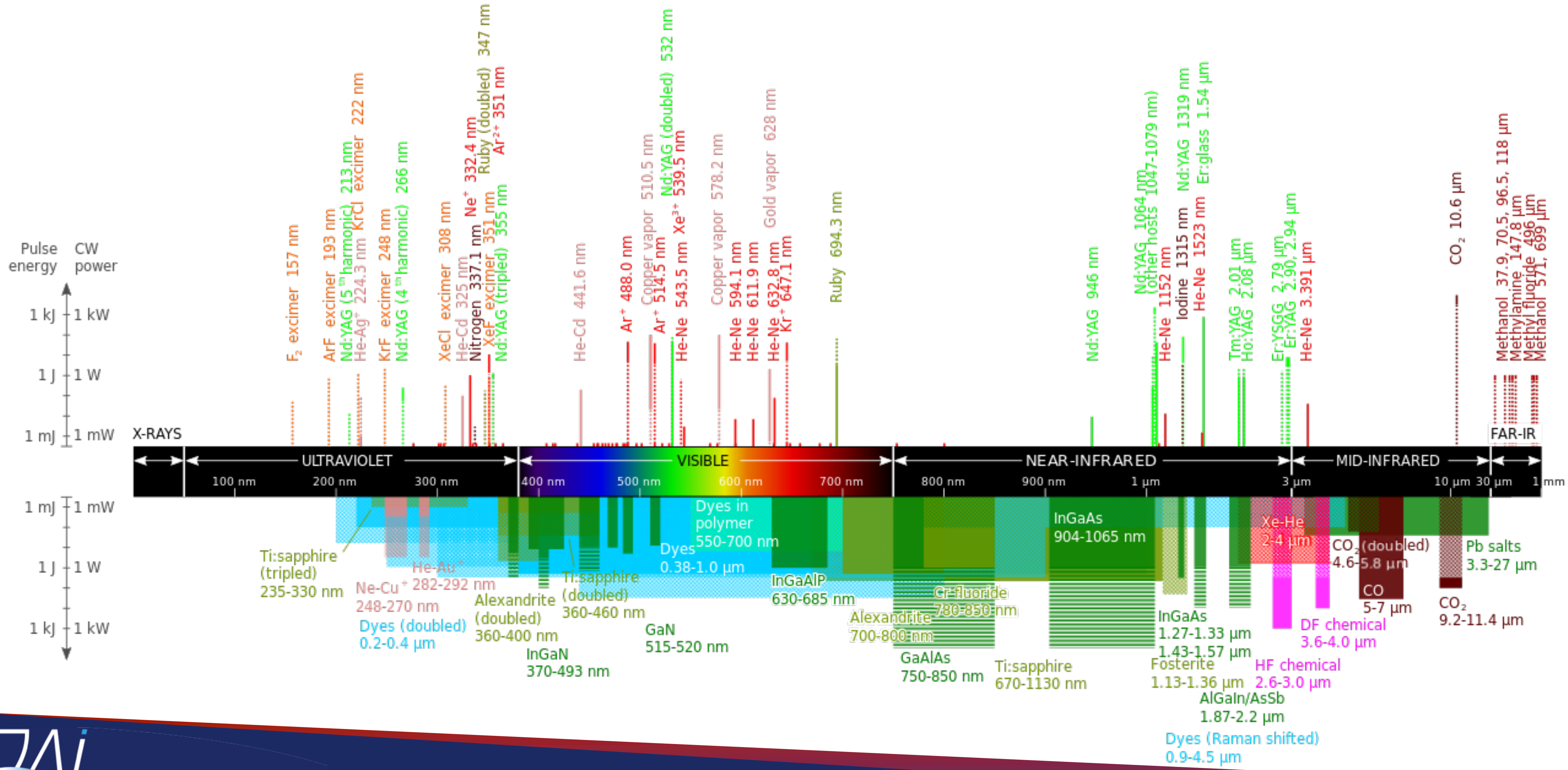
- *When selecting a laser you have a wide choice of technologies:*
  - *Gas lasers [HeNe, Argon, Krypton, CO_2…]*
    - *Chemical lasers [COIL, AGIL, HF, DF]*
    - *Excimer lasers: chemical reaction involving excited dimer [F_2, ArF, KrF, XeCl, XeF]*
    - *Ion lasers: [Argon-Ion]*
    - *Metal-vapour lasers: [HeAg, NeCu, HeCd for UV wavelengths …],*
  - *Solid state lasers [Ruby, Nd:YAG, Ti:sapphire …]*
  - *Semiconductor lasers [GaN, InGaN, VCSELs]*
  - *Fibre lasers (Erbium doped)*
  - *Free electron laser, etc…*



- *Many parameters to consider*
  - *Pulse energy, or continuous wave (CW) power?*
  - *Fixed or tuneable wavelength? Linewidth, spectral coherence?*
  - *Q-switched, repetition rate, mode-locked, master-oscillator power amplifier, free-space or fibre output?*
  - *Spatial beam quality, divergence, transverse modes, phase noise?*

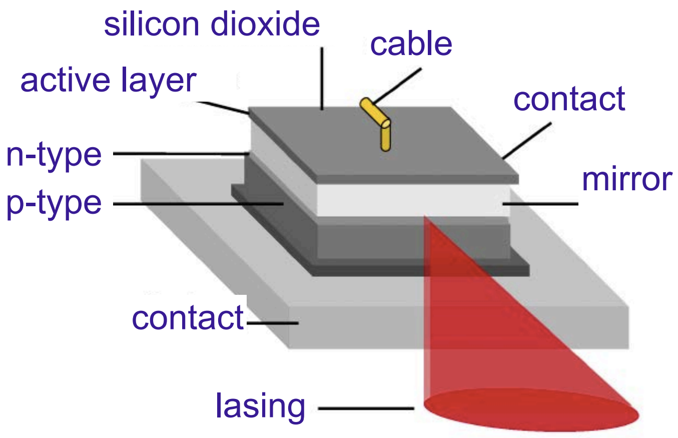
Laser types and key parameters

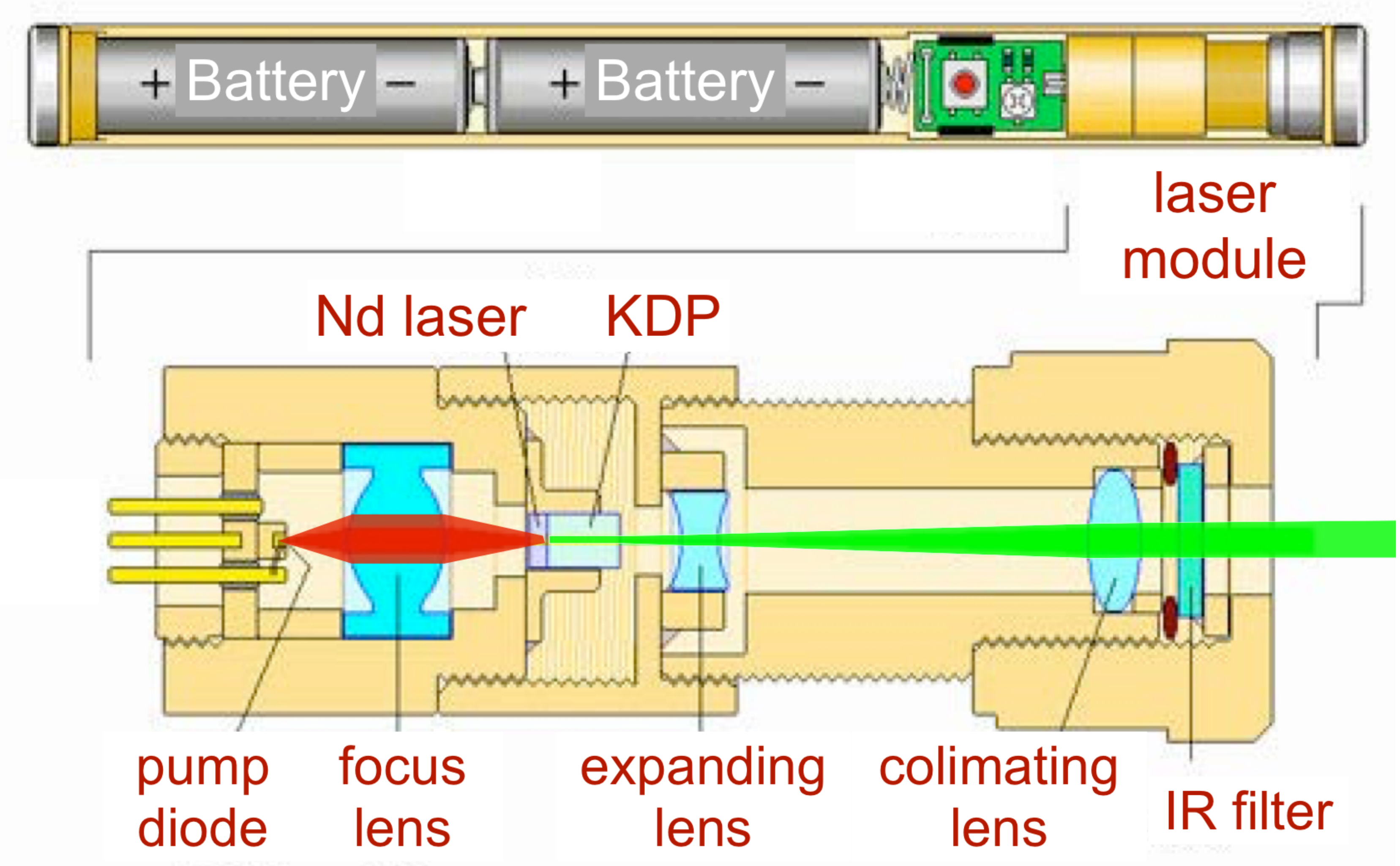
- *Lasers by wavelength, pulse energy / CW power:*



From the very small…

Semiconductor diode laser





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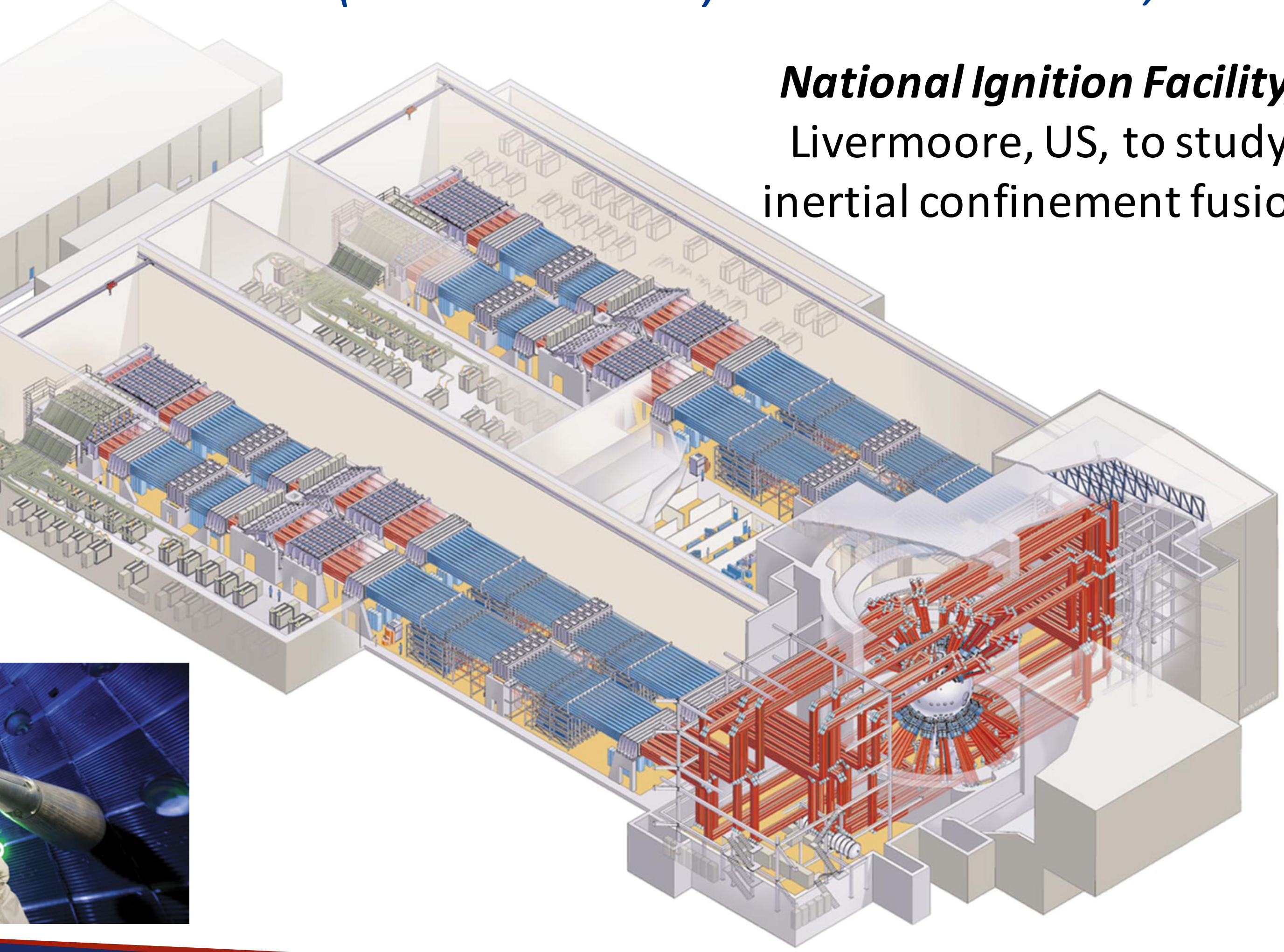
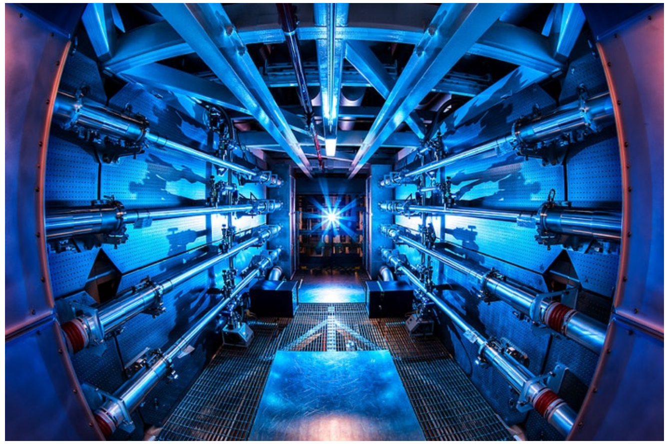
…to the very large

- *NIF aims to achieve single 500 terawatt (TW) peak flash of light that reaches the target from numerous directions (192 beamlines) at the same time, within a few picoseconds.*



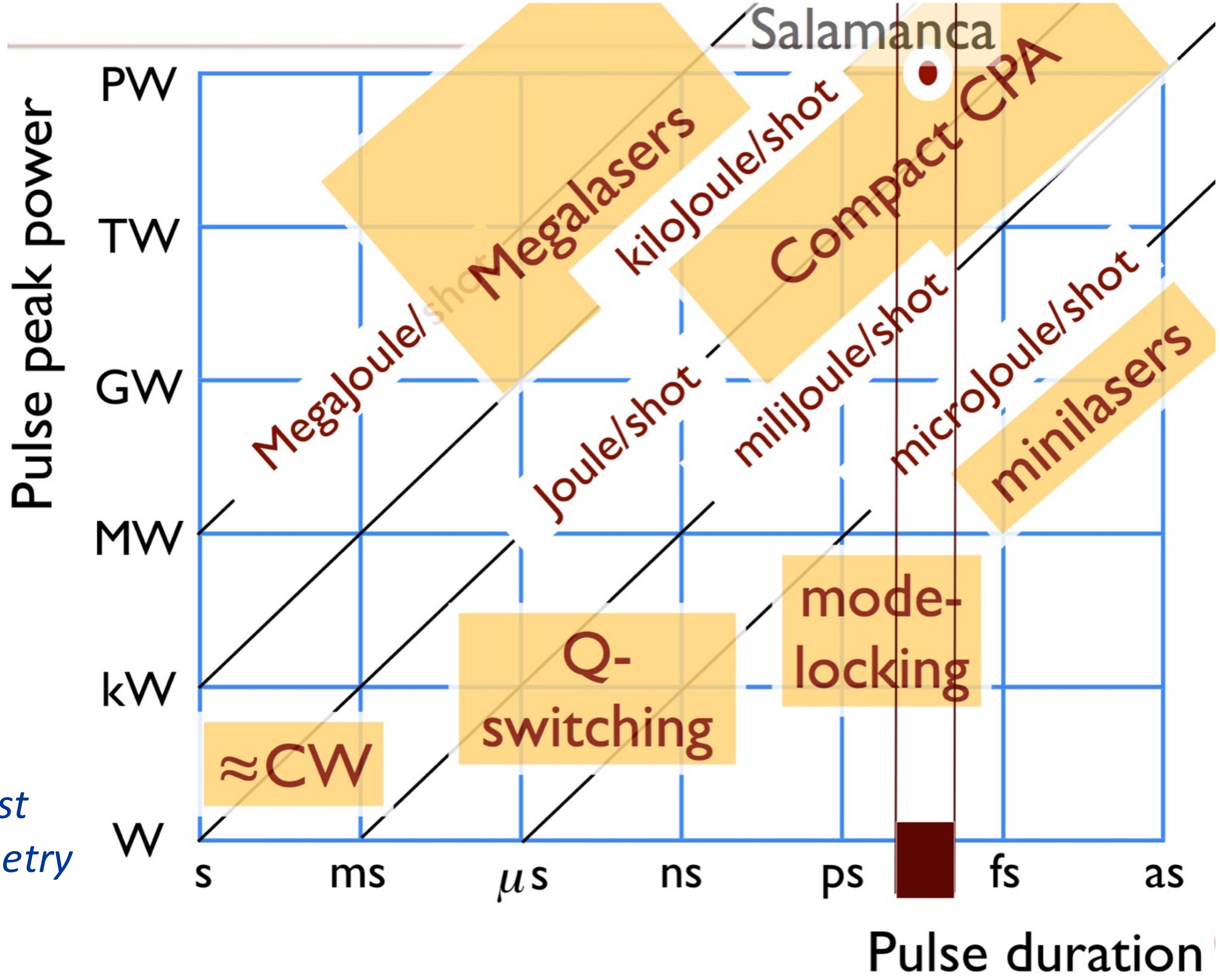
National Ignition Facility, Livermoore, US, to study inertial confinement fusion

Laser Bay 2 was commissioned in July 2007



What’s achievable?

- *Pulsed laser peak power vs duration: what’s achievable?*



Chirp Pulse Amplification
Pulse typically time stretched before amplification - later slides

Mode-locking
Short pulses generated by phase locking cavity modes – explained in later slides

Q-switched:
Pulse trains generated by electro-optic modulators within laser cavity.

Continuous Wave:
Narrow linewidth, modest power, good for interferometry

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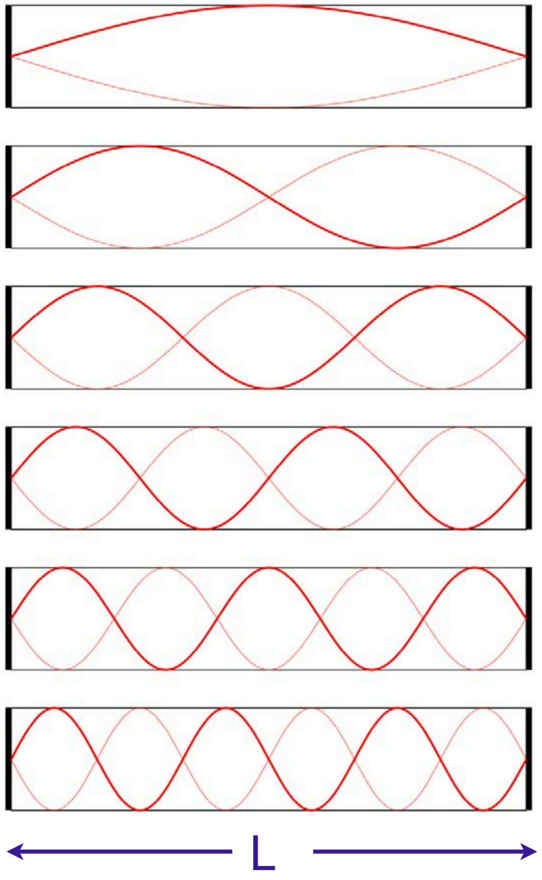
Optical Cavity Resonant Modes

- *An optical cavity enhances lasing only at certain resonant frequencies corresponding to longitudinal* modes allowed by the cavity length and mode number:*



Fundamental mode

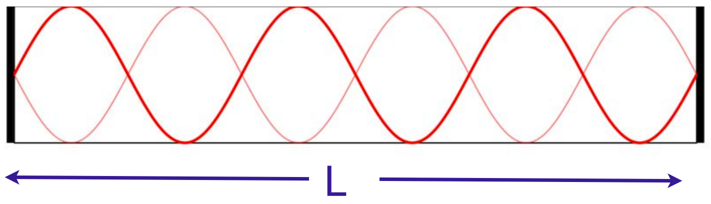
n=2

n=3

n=4

n=5

n=6



Electric field inside the cavity $E(z,t) = E_0 \cos(kz)\cos(\omega_L t)$

Boundary conditions $E(L,t) = E(-L,t) = 0$

Allowed wavelengths $n\lambda = 2L \qquad n = 1, 2, 3, \ldots$

Cavity modes $k = \frac{2\pi}{\lambda} = \frac{n\pi}{L}$

Resonant frequencies $\omega = kc = \frac{2\pi c}{\lambda} = n\frac{\pi c}{L}$

$$\nu_n = n\frac{c}{2L}$$

$$\nu_{n+1} = (n+1)\frac{c}{2L}$$

Consecutive frequencies

$$\Delta\omega = \omega_{n+1} - \omega_n = \frac{\pi c}{L}$$

** See next slide*

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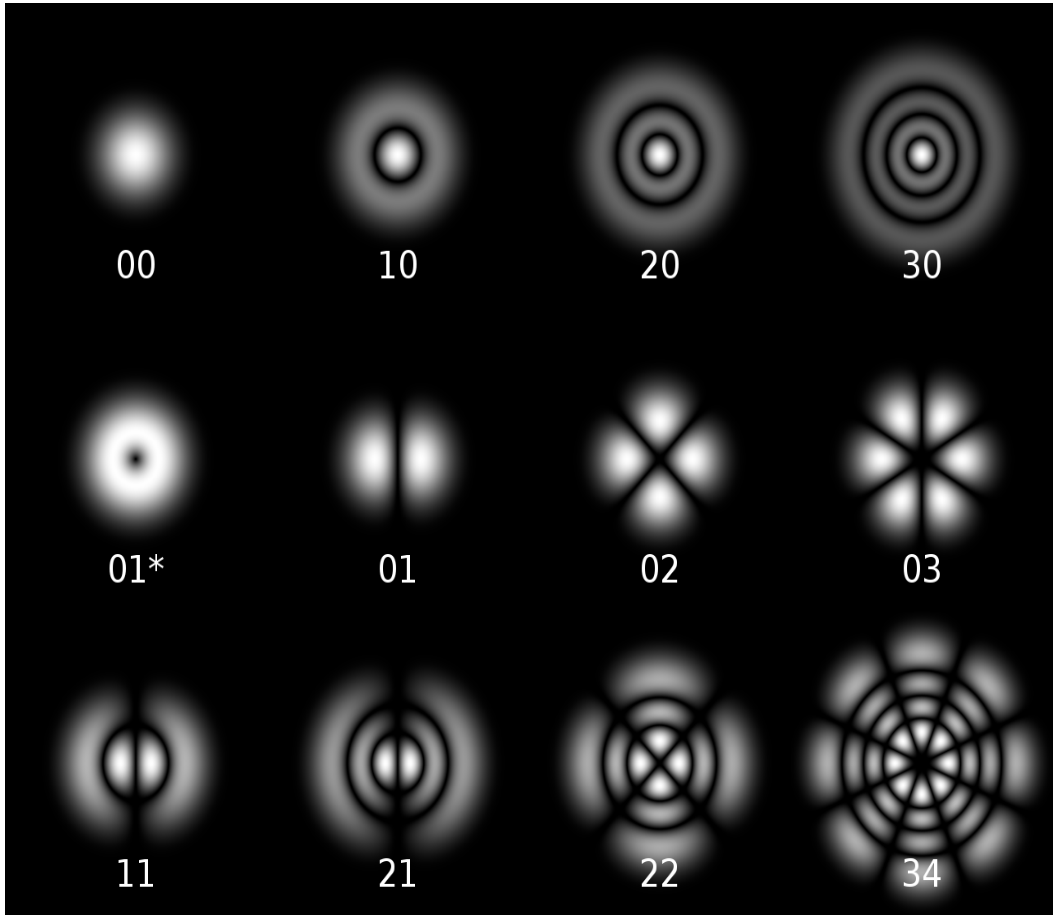
Optical Cavity Resonant Modes

- *Transverse TEM-NN modes in a cylindrical cavity:*

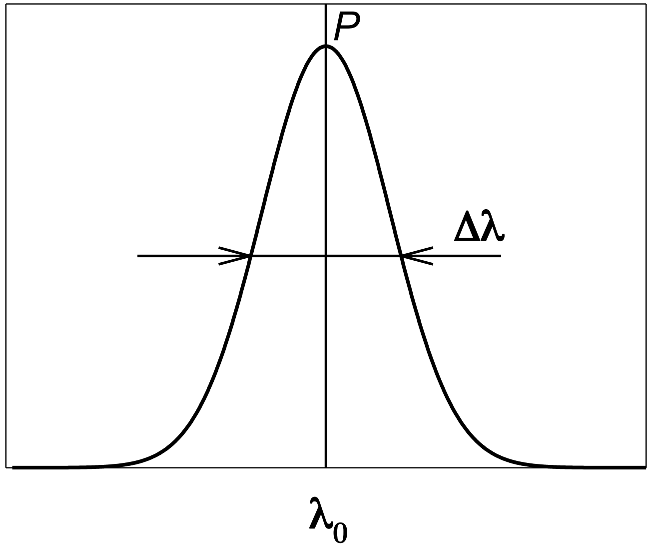


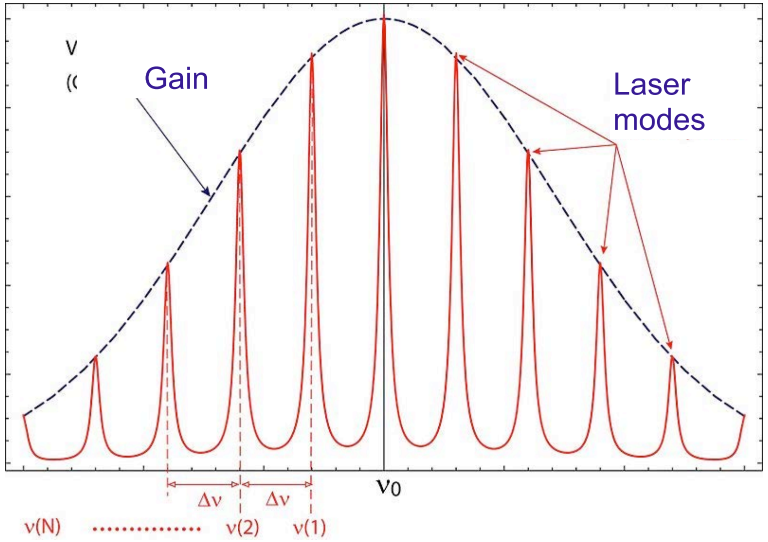
- *Laguerre-Gauss modes for a cylindrical boundary conditions*
- *By placing a restrictive aperture in the cavity, the fundamental transverse TEM00 mode is selected, resulting in a Gaussian output beam*

Laser linewidth (spectral coherence)

- *Although lasers are nearly monochromatic, they do not emit at a single, pure frequency, but produce light with a natural bandwidth or range of frequencies.*
- *Primarily, the bandwidth is determined by energy levels of the gain medium and the corresponding range of frequencies that can be amplified.*
- *Within this range, the optical cavity length defines the frequencies modes that are excited*
- *Usually a laser will emit at multiple modes simultaneously "multi-moded lasing".*

Laser type	λo	Δλ	λo/Δλ
He-Ne laser	632.5nm	0.2nm	3162.5
Diode Laser	900nm	10nm	90





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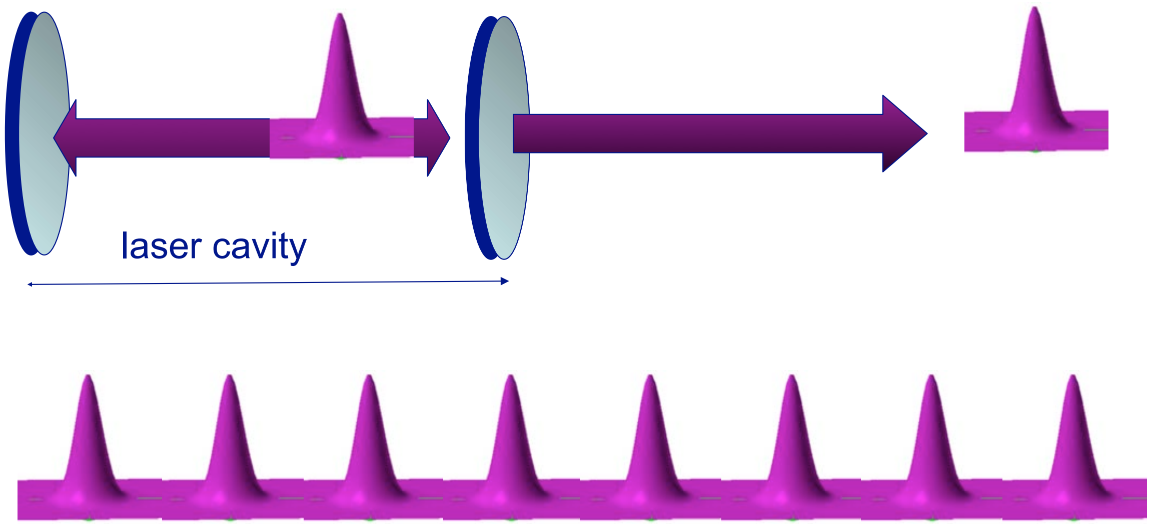
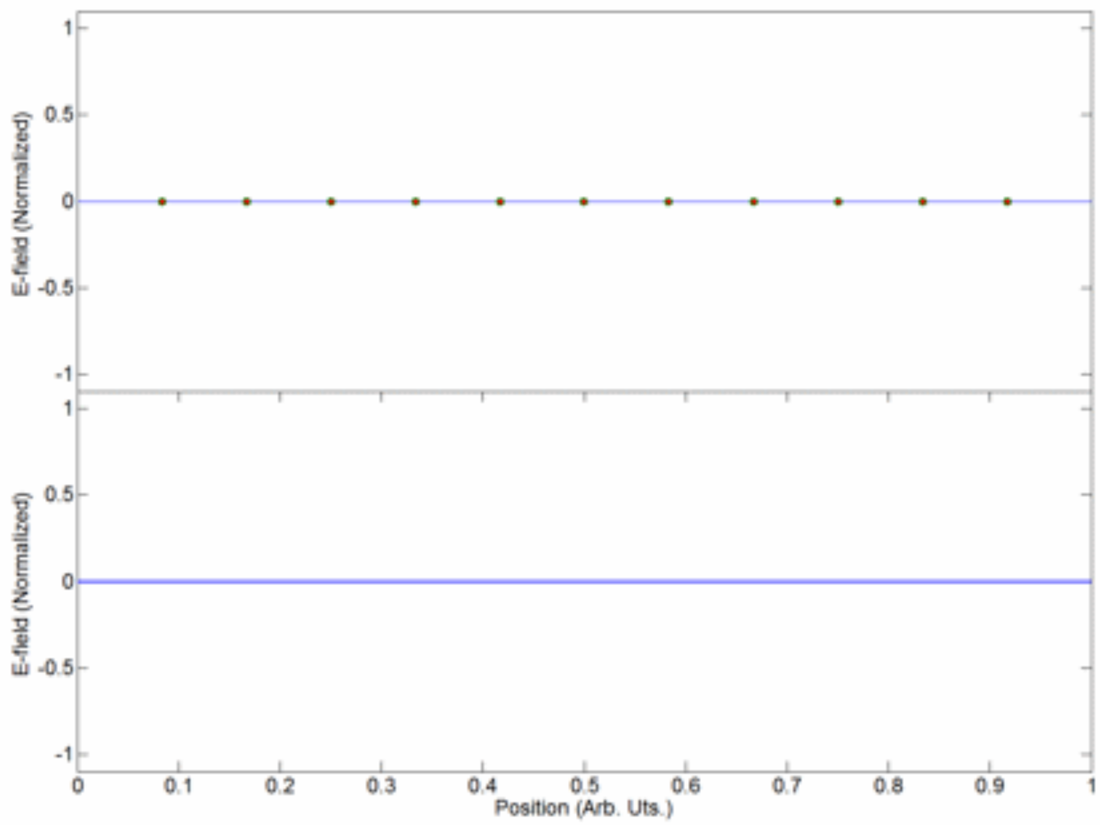
Mode-locking lasers

- *If cavity modes are phase-locked then a pulse can be generated in each round trip of the cavity*
- *Ultrashort pulses imply many modes in phase:*
  - *One picosecond implies a 1nm bandwidth*
  - *10 femtoseconds imply 100 nm (almost all visible)*





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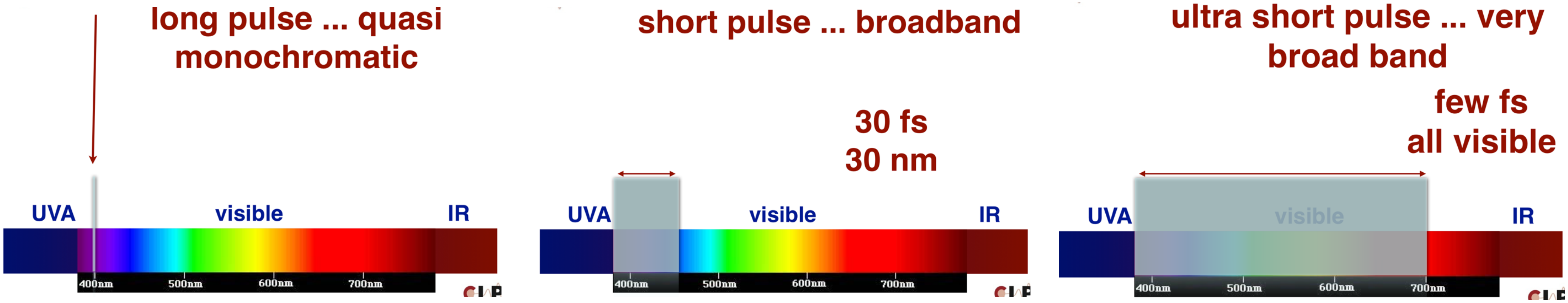
Short pulses ⟷ Broadband

- *There's an inverse relation between the pulse duration and bandwidth.*
- *Shorter duration pulses have larger frequency 'chirp'*



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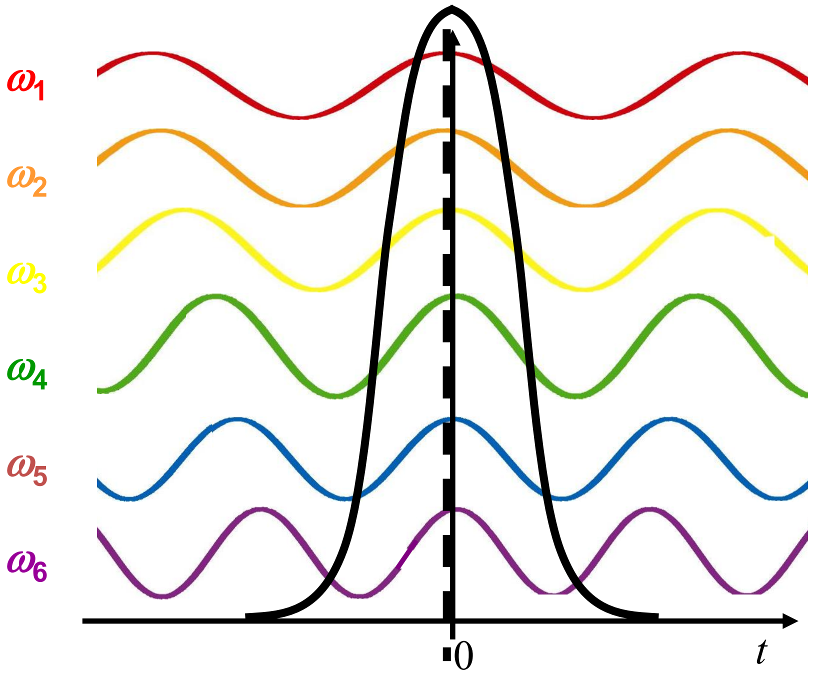
Chirped laser pulses:

- *See Alan Gillespe's slides from this morning*

Effect of the Spectral Phase

The spectral phase is the phase of each frequency in the wave-form.



All of these frequencies have zero phase. So this pulse has:

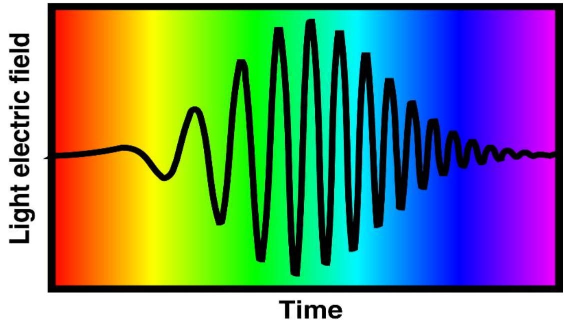
$\varphi(\omega) = 0$

Note that this has constructive interference at $t = 0$.

..and it has cancellation everywhere else.

"*Transform limited pulse*" – cannot get any shorter for the given spectral content

A linearly chirped Gaussian pulse



We can write a linearly chirped Gaussian pulse as:

$$E(t) = E_0 \exp\left[-(t/\tau_G)^2\right] \exp\left[i\left(\omega_0 t + \beta t^2\right)\right]$$

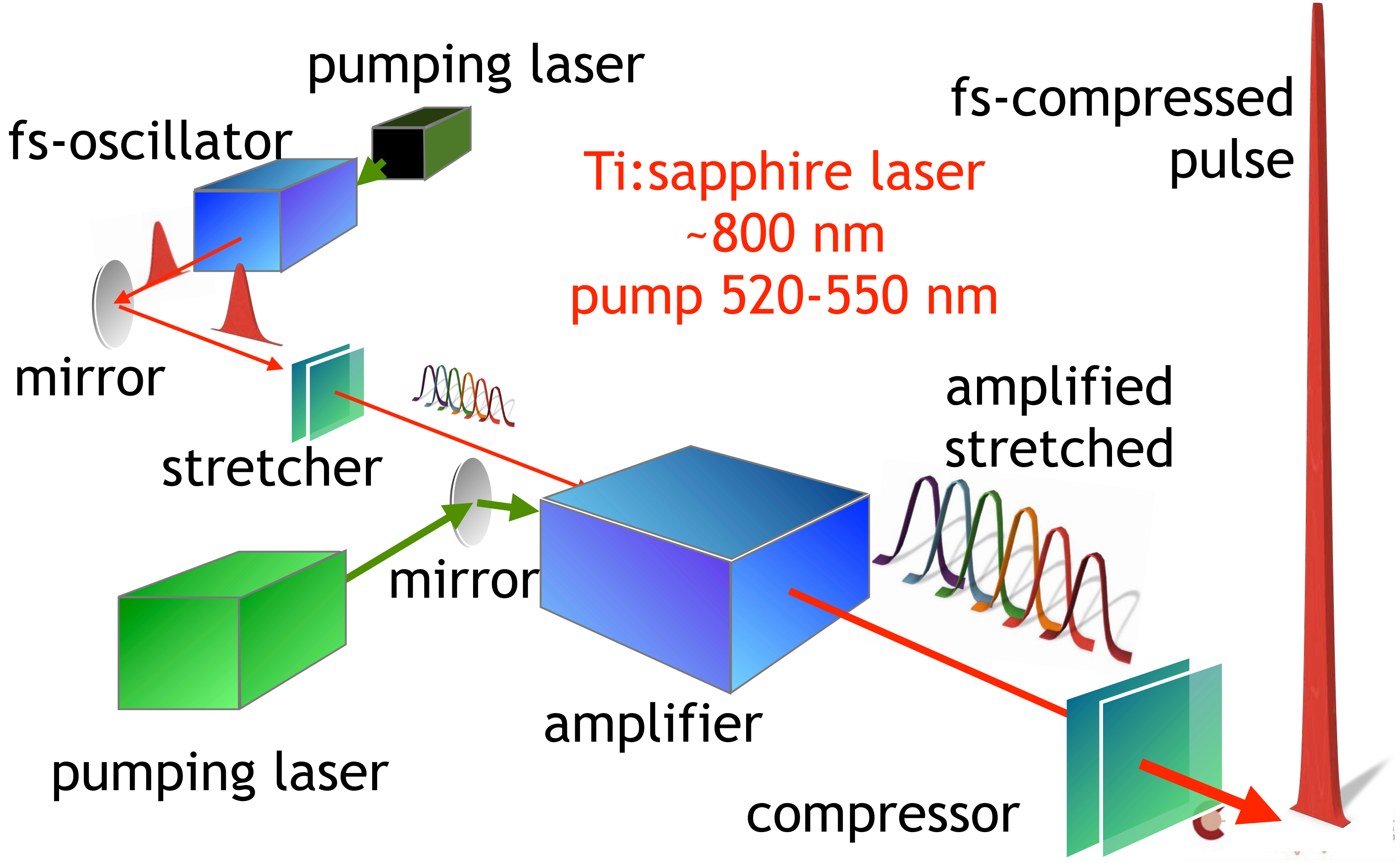
Gaussian amplitude

Carrier wave

Chirp

Note that for $\beta > 0$, when $t < 0$, the two terms partially cancel, so the phase changes slowly with time (so the frequency is lower). And when $t > 0$, the terms add, and the phase changes more rapidly (so the frequency is larger).

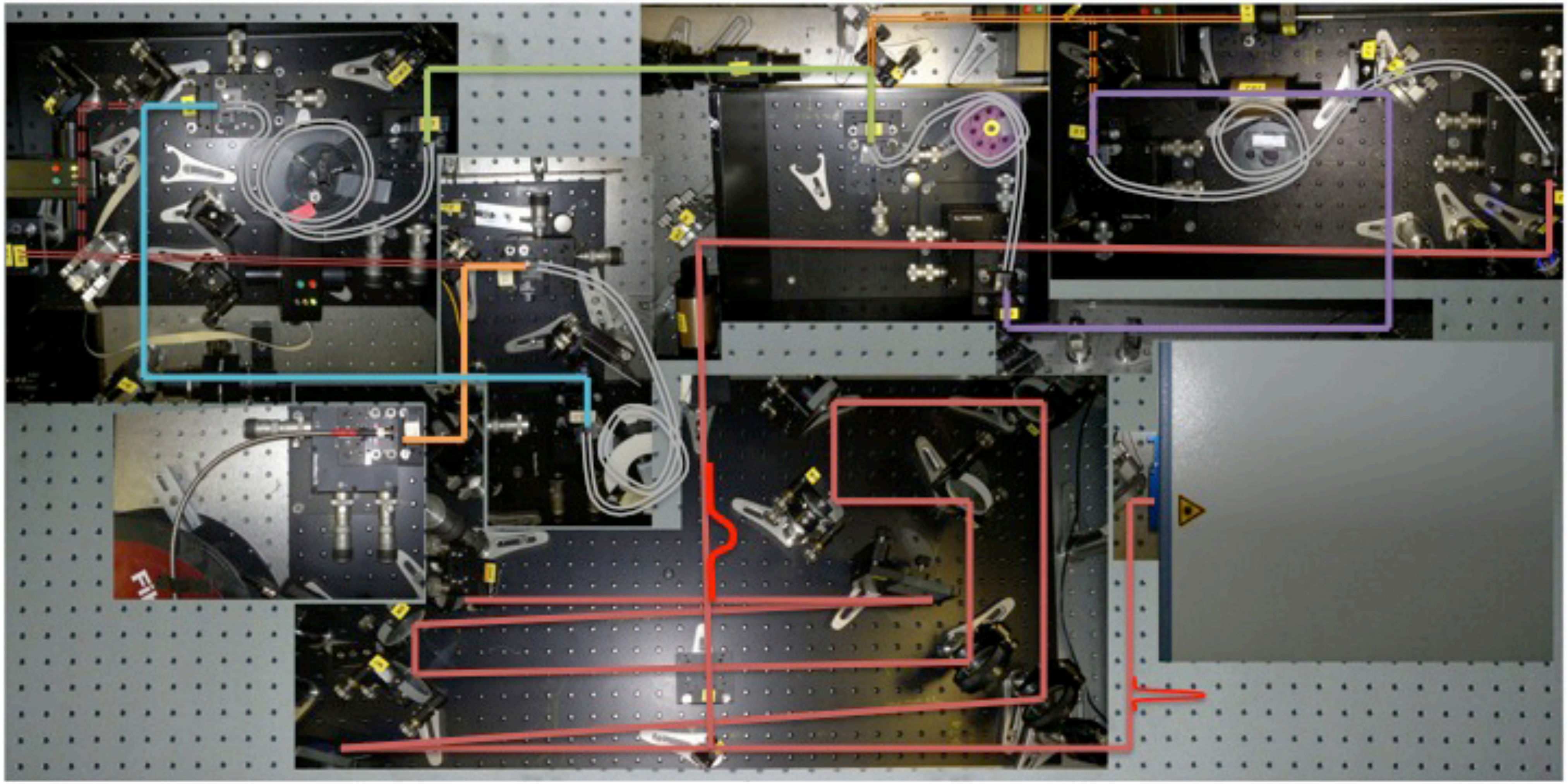
Chirp pulse amplification concept



Intro to lasers, Lui Roso 1st LA³net school

Chirp pulse amplification at Petra-III laserwire

Laser oscillator is a Nd:YVO4 solid state mode-locked oscillator emitting laser light at 1064 nm



At laser:

Parameter	Value
Wavelength	1064 nm
Pulse Duration (FWHM)	10 ps
Repetition Rate	62.45 MHz
Average Power	850 mW
Pulse Energy	13.5 nJ
Peak Power	1.3 kW

After ***pulse stretching*** and ***4 stage fibre amplification***

Parameter	Value
Wavelength	1064 nm
Pulse Duration (FWHM)	200 ps
Repetition Rate	520 kHz
Average Power	1.5 W
Pulse Energy	2.9 uJ
Peak Power	14 kW

A. Bosco et al, RHUL/DESY

How to synchronize the rep rate of a pulsed laser with RF timing?

- *If ~10ps laser pulses are to interact with the particle bunches the repetition rate of master oscillator needs to be carefully synchronised with the accelerator RF and with minimal timing jitter.*

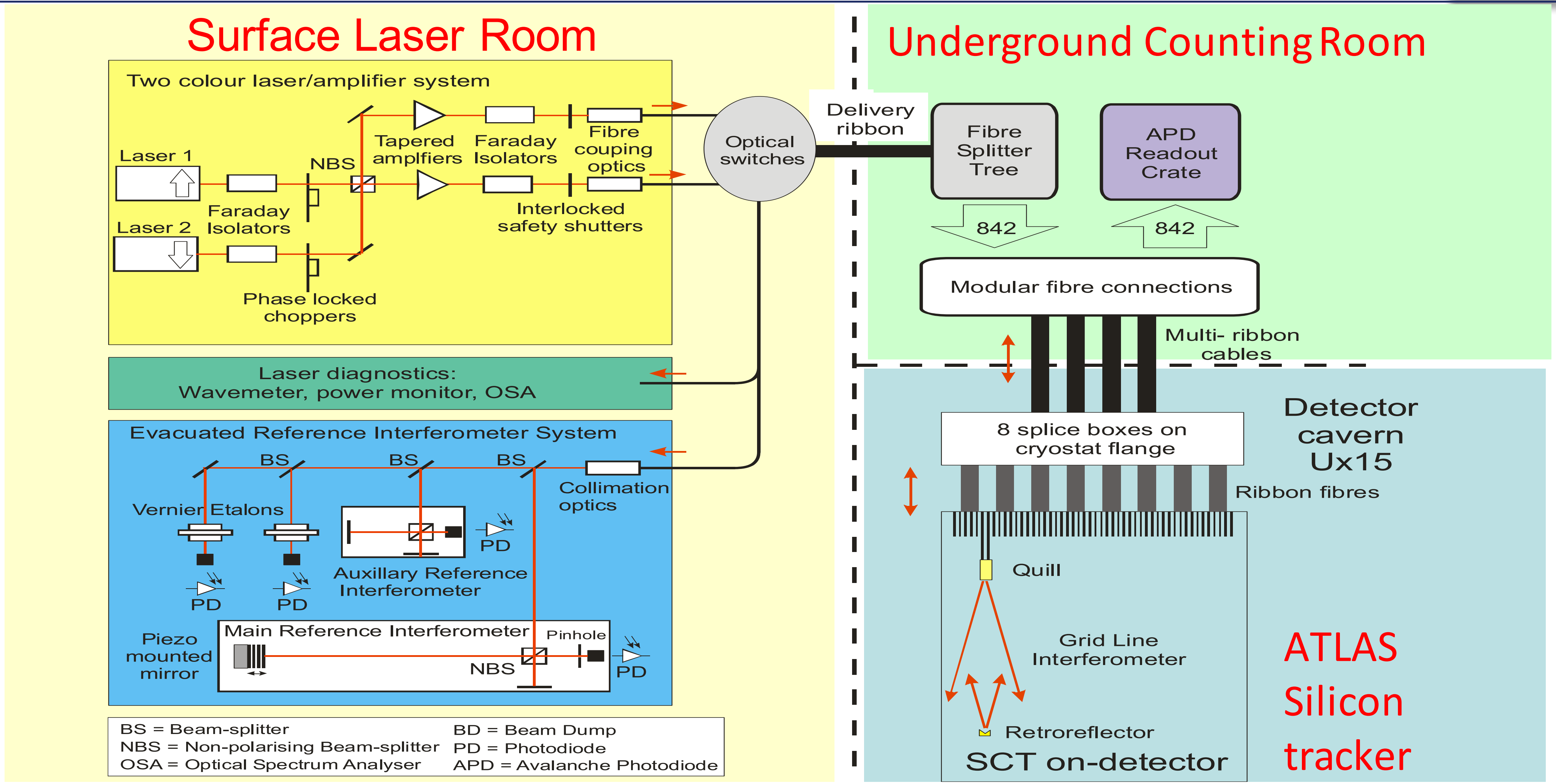
- *Synchronization achieved by using an external RF generator that is set to a subharmonic of the accelerator RF frequency (499.664 MHz).*
  - *Compare phase between the laser pulse train and external RF.*
  - *Feedback loop controls a moveable mirror within the laser cavity, modifying the cavity length to change the repetition rate of until a phase lock with the RF source is achieved.*
  - *Finally lock the phase between the main clock to a low noise (10MHz) reference from the accelerator RF timing.*

A. Bosco et al, RHUL/DESY

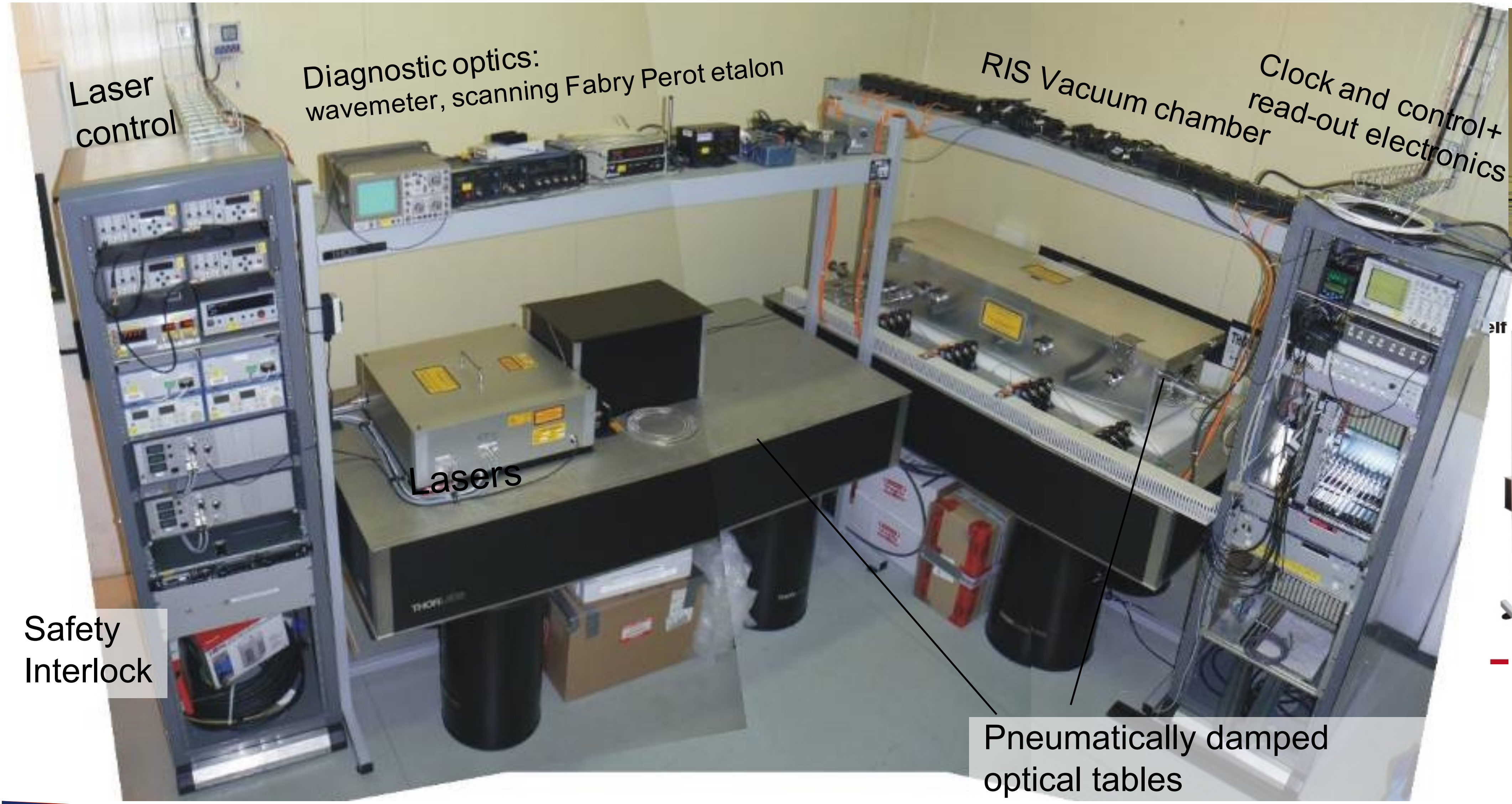
Setups: Beam transport for lasers at accelerators

- *Lasers are sensitive and occasionally temperamental beasts; best to keep in a safe laser cabin, away from the accelerator tunnel:*
  - *Easy access to laser.*
  - *Safety requirements: interlocks, safety shielding, googles, warning signs.*
  - *Reduce radiation exposure to laser and personnel.*
  - *Enable thermal stabilisation of environment and vibration free.*
- *Must therefore transport the laser beam to the accelerator tunnel, two viable options:*
  - *Free space beam via series of mirrors, and tubes:*
    - *challenging beam pointing requirements, especially if tubes contain air, suseptible to refractive index change)*
    - *May be only option if very high power is required.*
  - *Transport in* optical fibres*:*
    - *Easy to install.*
    - *Limits on peak power / pulse duration due to non-linear effects in the fibre.*

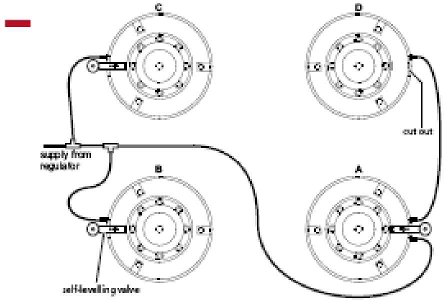
Example of CERN laser setup: FSI system at ATLAS



Example of CERN laser setup: surface room for laser

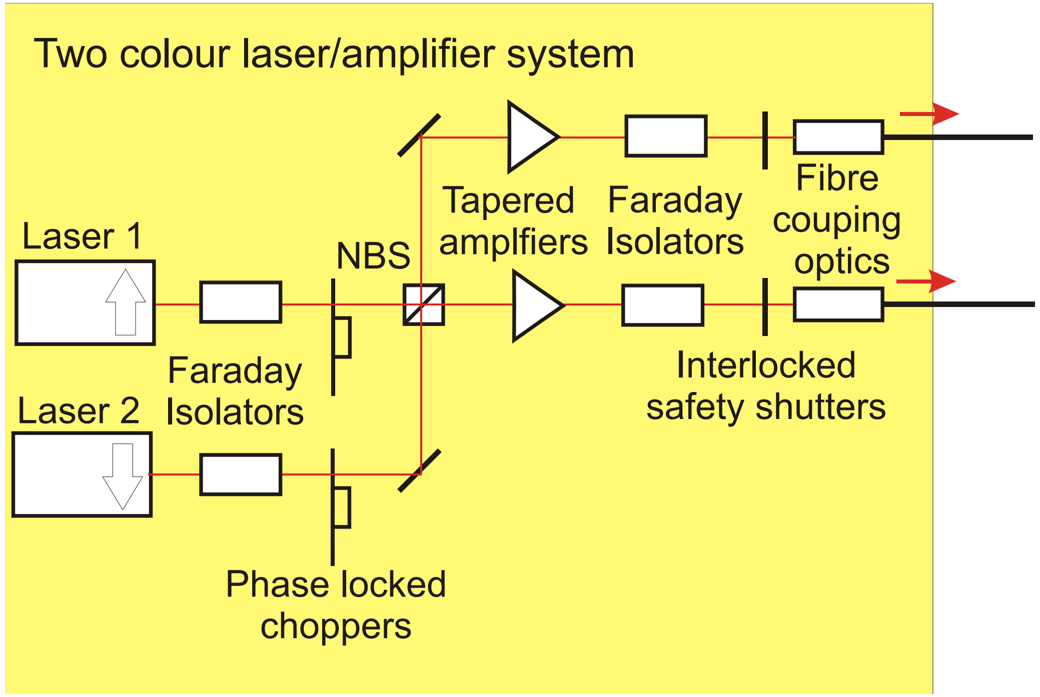


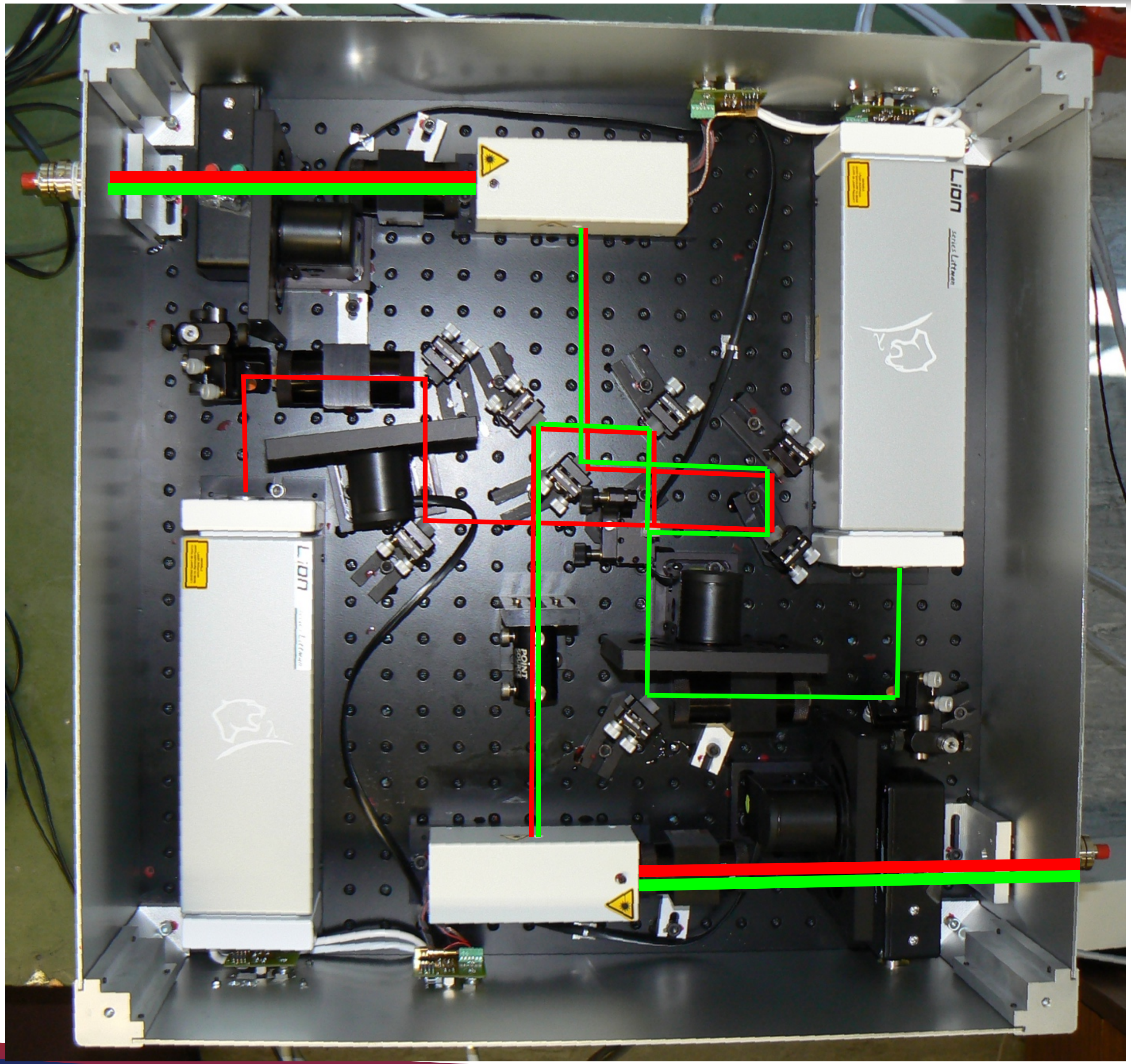
Thermally stabilised



Example of CERN laser setup: two colour amplifier system

- *Two CW tunable lasers combined into two tapered amplifiers*
- *Phase locked choppers.*
- *Coupled to fibres to underground*





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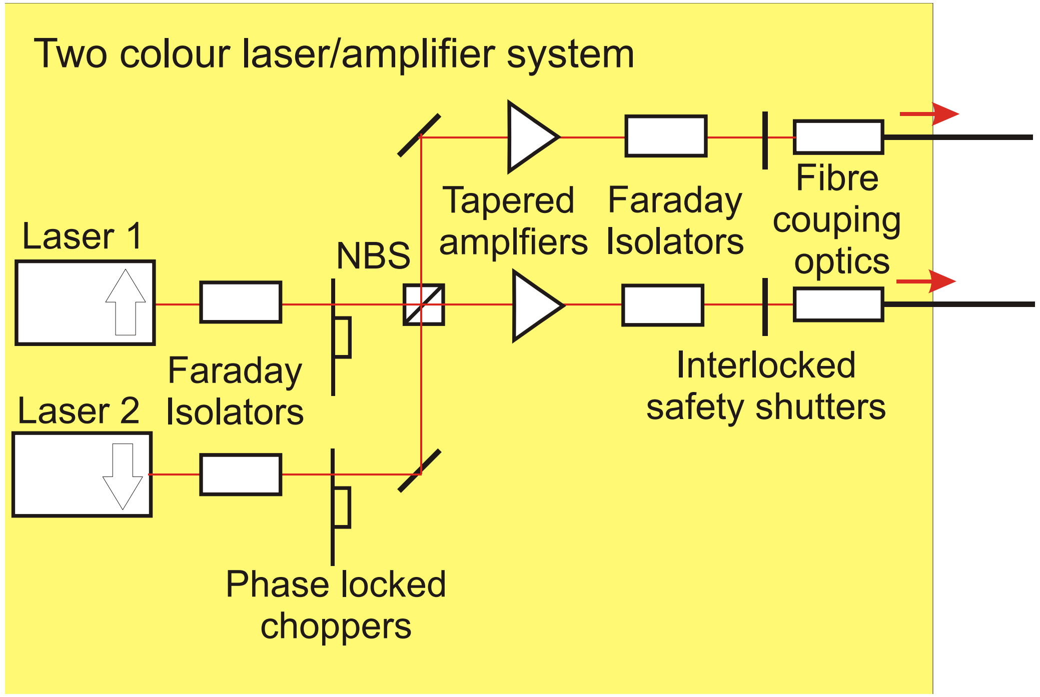
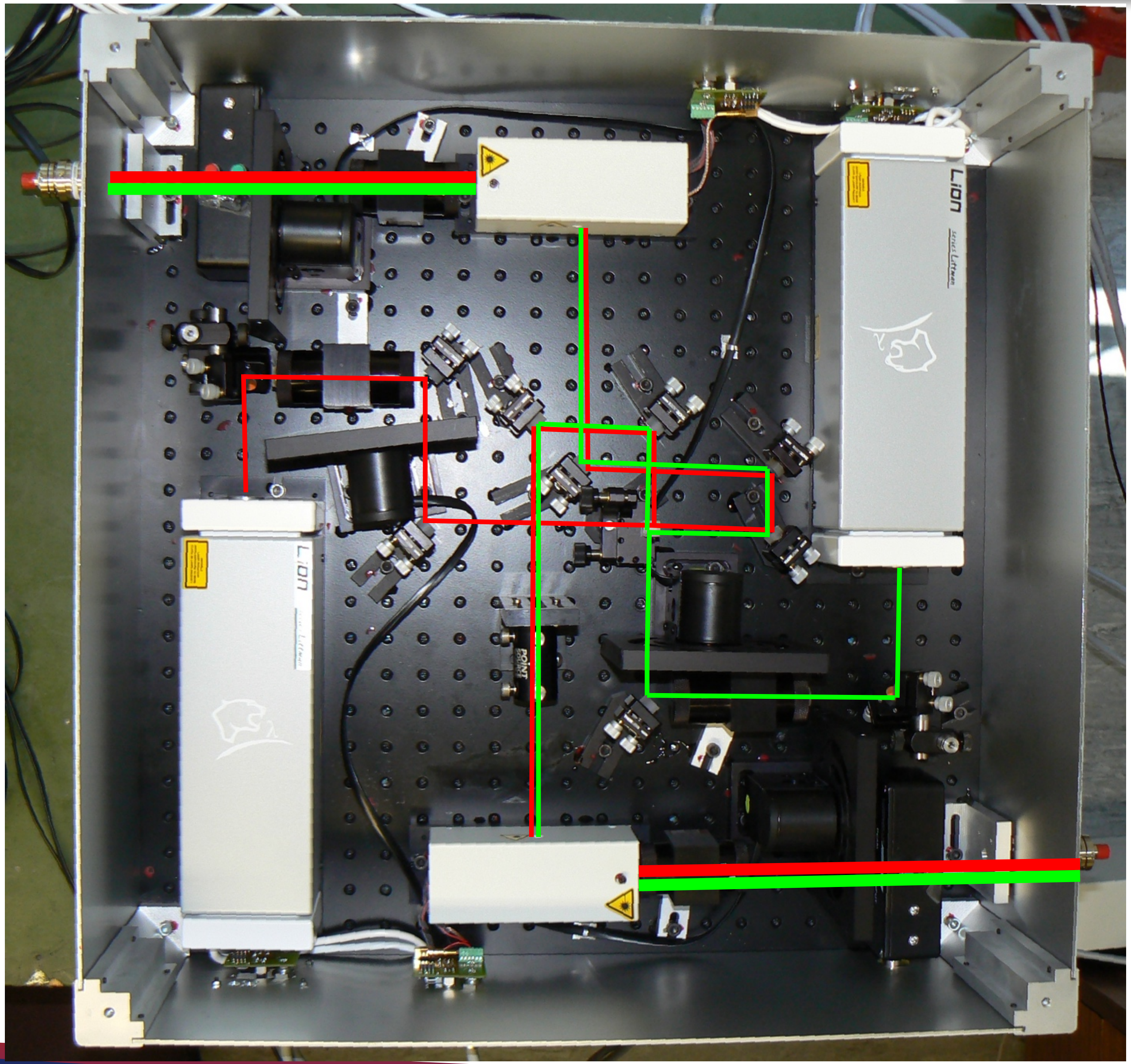
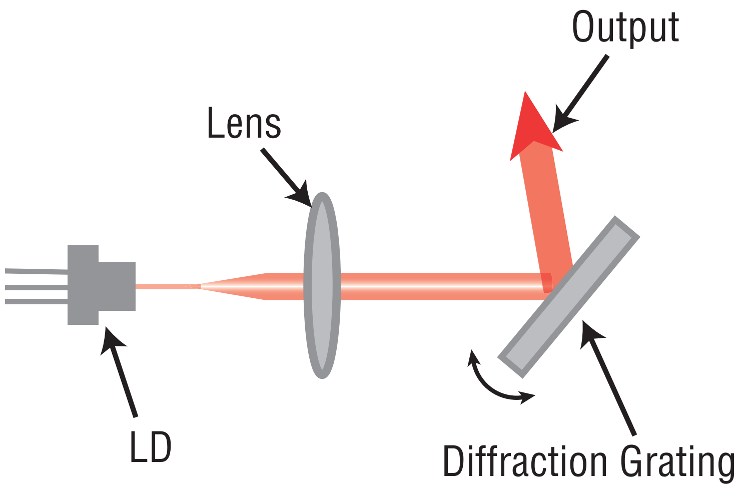




Frequency tunable lasers

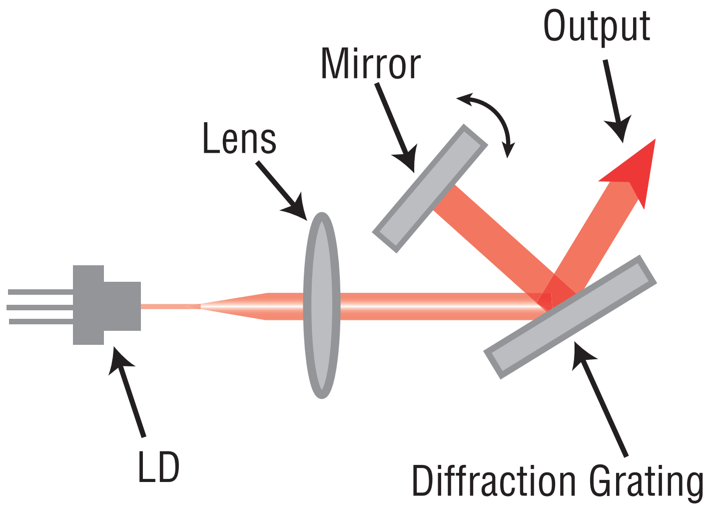
- *CW tunable external cavity diode lasers (ECDL) are design to select a* ***single mode*** *using wavelength selective optics.*
- *Two configurations:*

Littrow



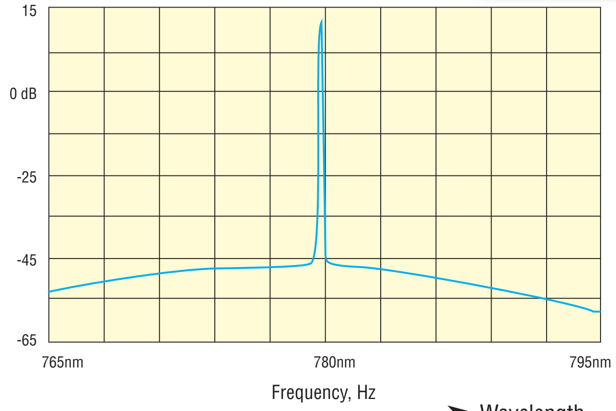
Higher power, broader linewidth

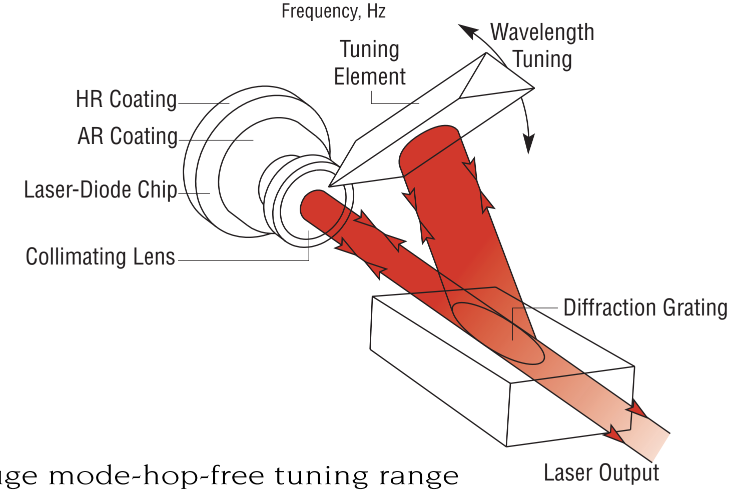
Littman-Metcalf



Very narrow, <200kHz linewidth

Wide mode-hop free tuning (>10nm).





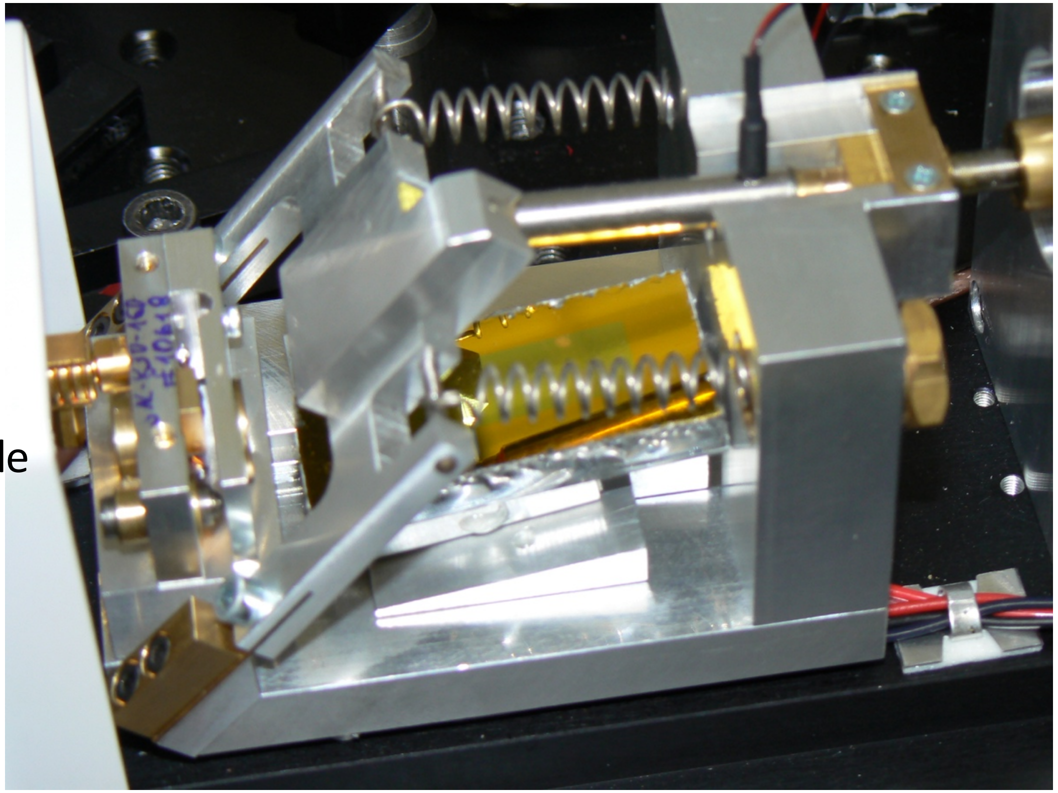
- Huge mode-hop-free tuning range
- Motorized and Piezo control for wide scanning and fine tuning
- Higher power
- Improved stability, <200 kHz linewidth
- Integrated permanent fiber coupling

New Focus™ A Newport Corporation Brand

Frequency tunable lasers

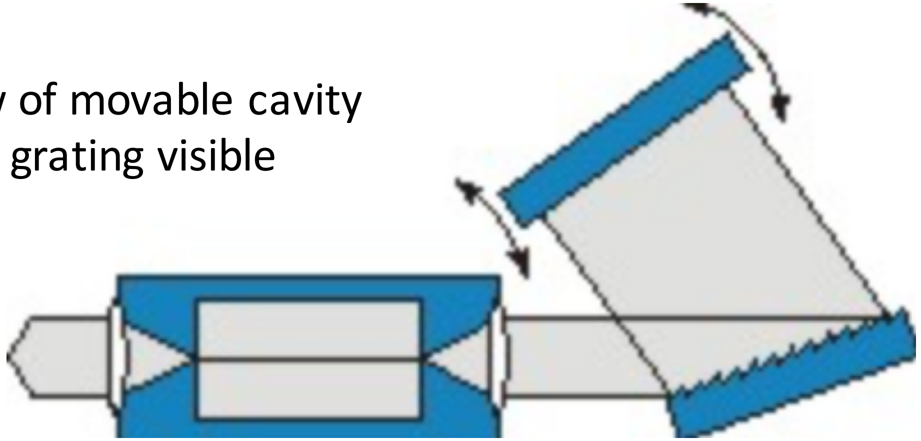
- *CW tunable external cavity diode lasers (ECDL) are design to select a* ***single mode*** *using wavelength selective optics.*

Laser diode



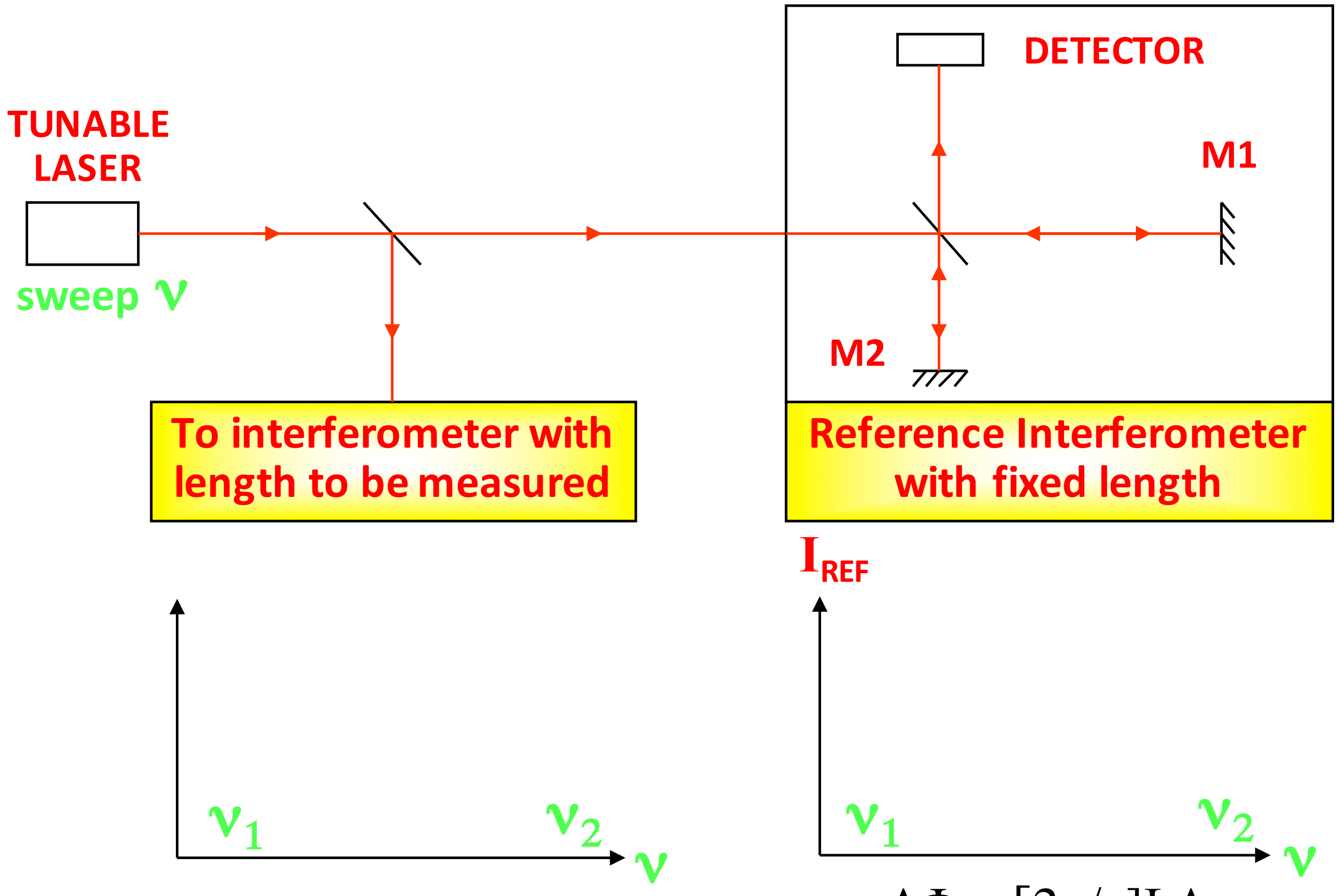
Littman-Metcalf

View of movable cavity with grating visible



Similar to tunable laser used in Electro-Optic Beam Position Monitor (see applications lecture)

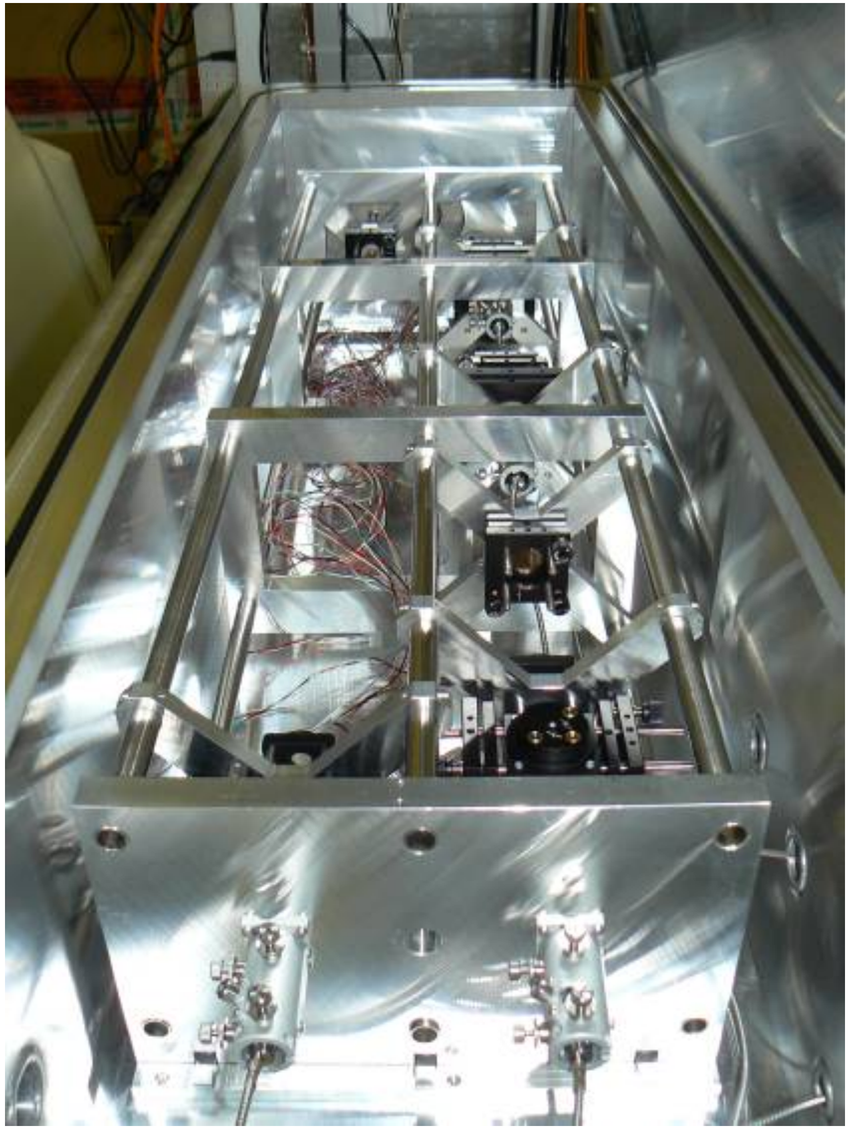
Frequency Scanning Interferometry



$$\Delta\vartheta = [2\pi/c]D\Delta\nu$$

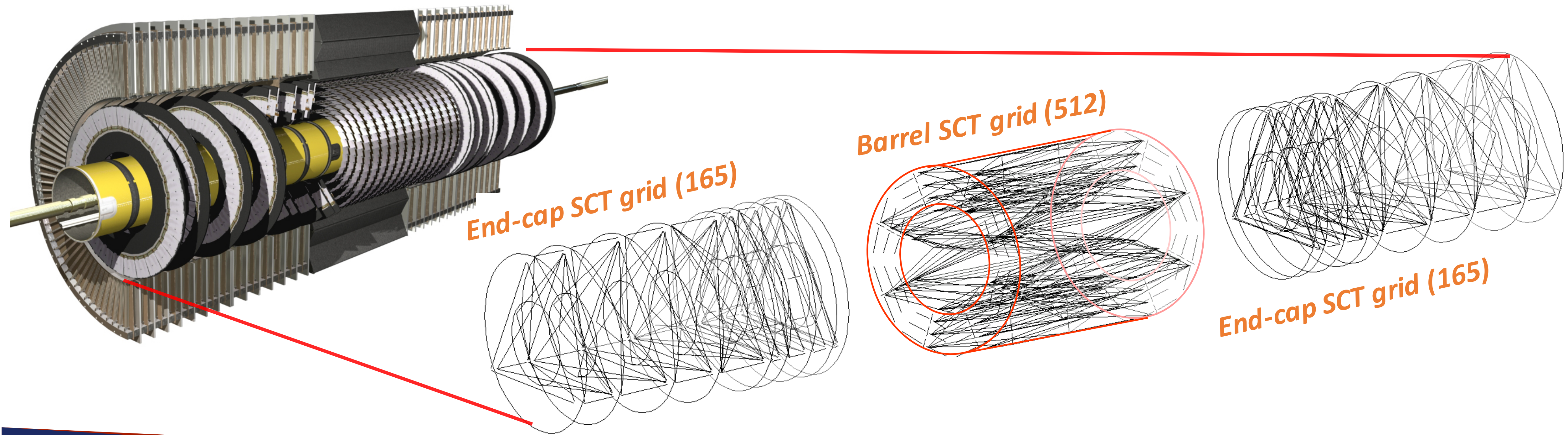
$$\Delta\Phi = [2\pi/c]L\Delta\nu$$

Ratio of phase change = Ratio of lengths



ATLAS FSI 842 x inteferometer system

- *The ATLAS silicon tracker is equipped with a laser alignment system consisting of geodetic length measurements between nodes.*
- *All 842 grid lines are measured simultaneously using FSI to a precision of << 1 mm.*
- *Repeated measurements monitor micron level shape changes of the SemiConductor Tracker (SCT) during operation*



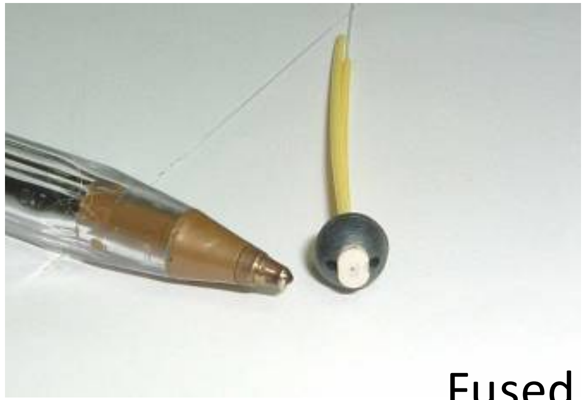
Challenges of particle accelerator environment

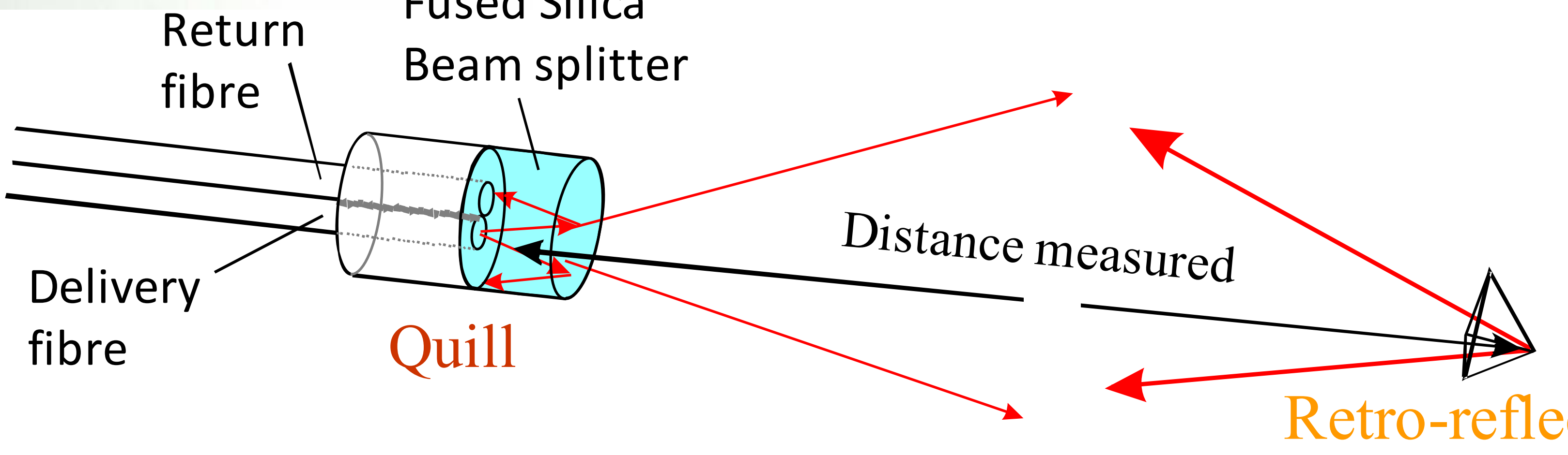
- *On-detector ATLAS FSI system has similar requirements to Accelerator Beam Instrumentation:*

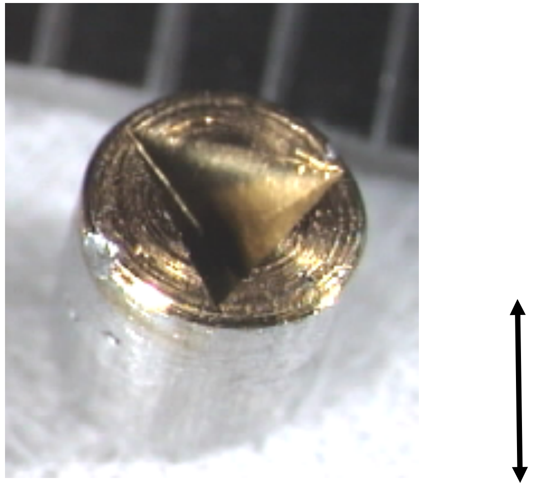
- *Often available space in a PP experiment / accelerator is extremely limited.*
- *Components must also tolerate high radiation levels:*
  - *Use radiation hard plastics, PEEK, fused silica, radiation tolerant fibres: e.g. pure silica core, fluorine down doped cladding.*
- *No access throughout the >10 year operational lifetime of the experiment: Optics must be robust to any small misalignments, e.g. use diverging beams and retroreflectors.*

Fibre based grid-line Interferometer

- *Each length measurement line of the alignment grid inside the SCT consists of a quill (two parallel fibres and a beam splitter) and a retro-reflector.*
- *The optical path difference is measured. GLI lengths vary from 40mm to 1500mm*

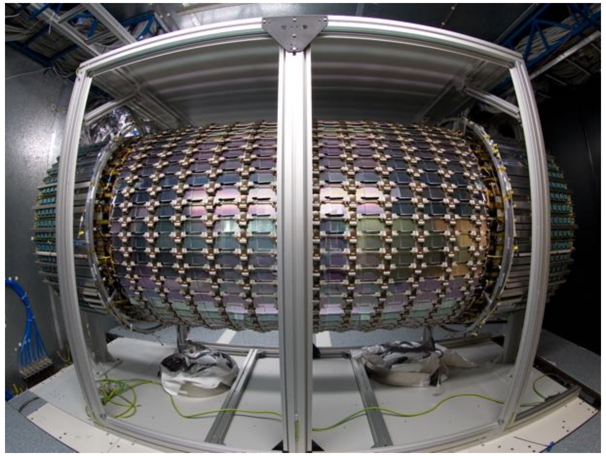


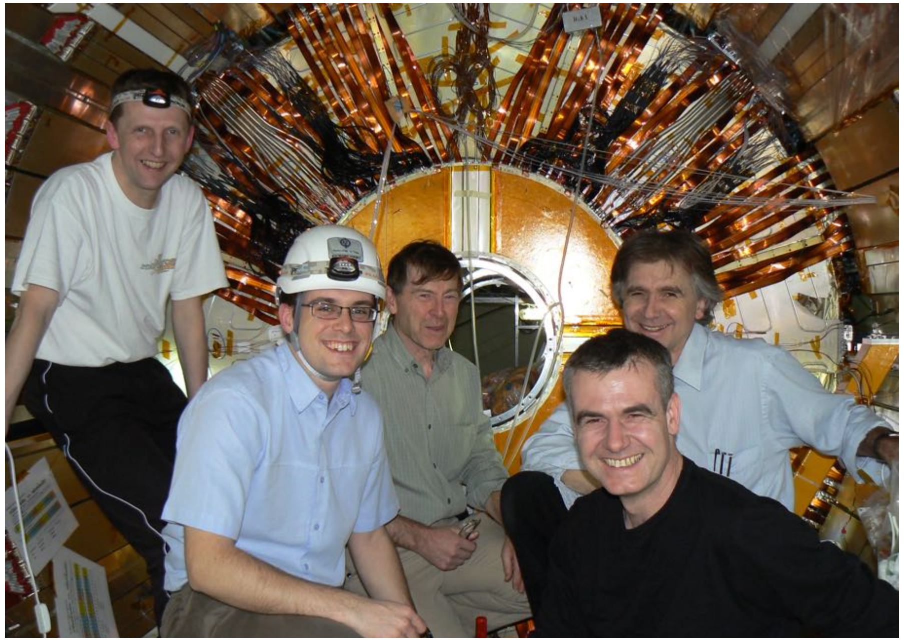




2.3 mm diameter

Construction of FSI system

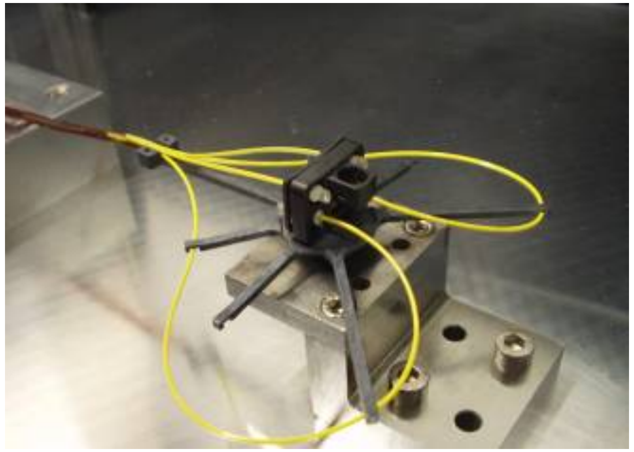


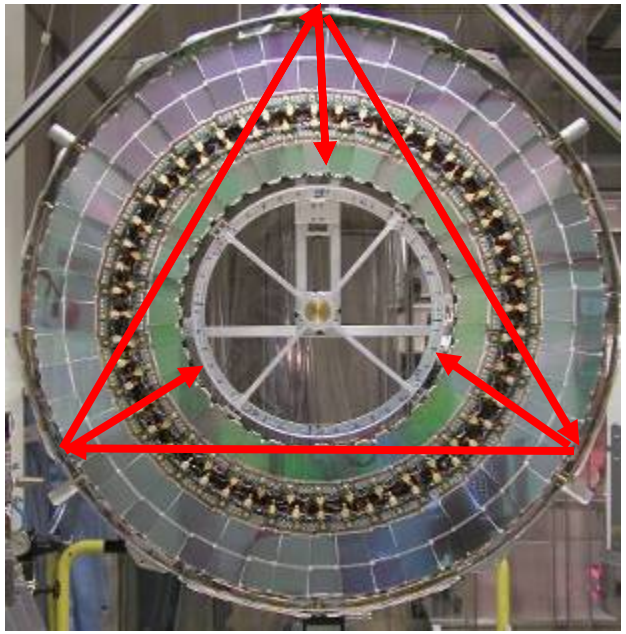


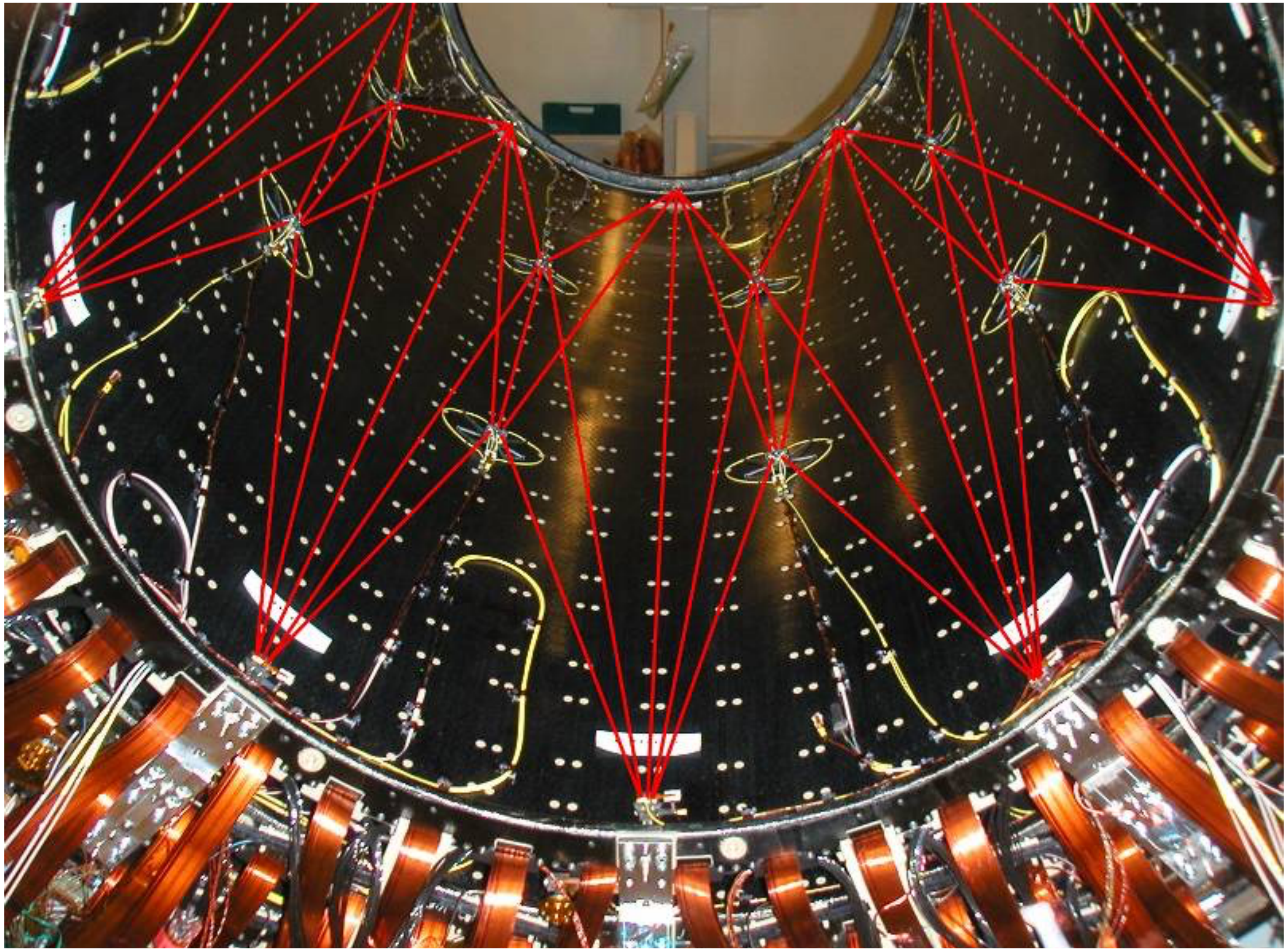
Installing delicate fibres inside the centre of ATLAS for Frequency Scanning Interferometry alignment system

-> ***precise optical metrology***

FSI grids on ATLAS SCT







Fibre coupling solutions:

- *Obtaining good coupling (>70%) from the laser is often one of the main practical challenges*
- *In this case also needed to couple light from one laser to 842 interferometers.*

- *First focus >300 mW CW light into a 5 micron core single mode fibre.*

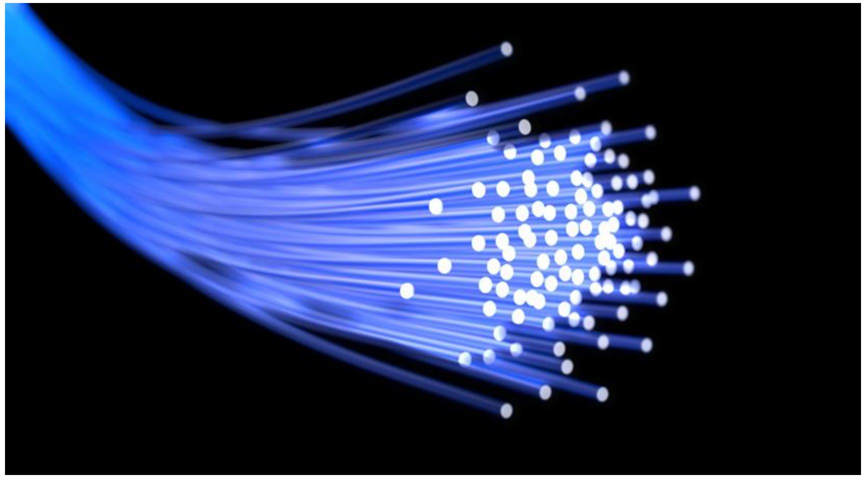
Laser may be installed with a fibreport: 3+2 DoF adjustment

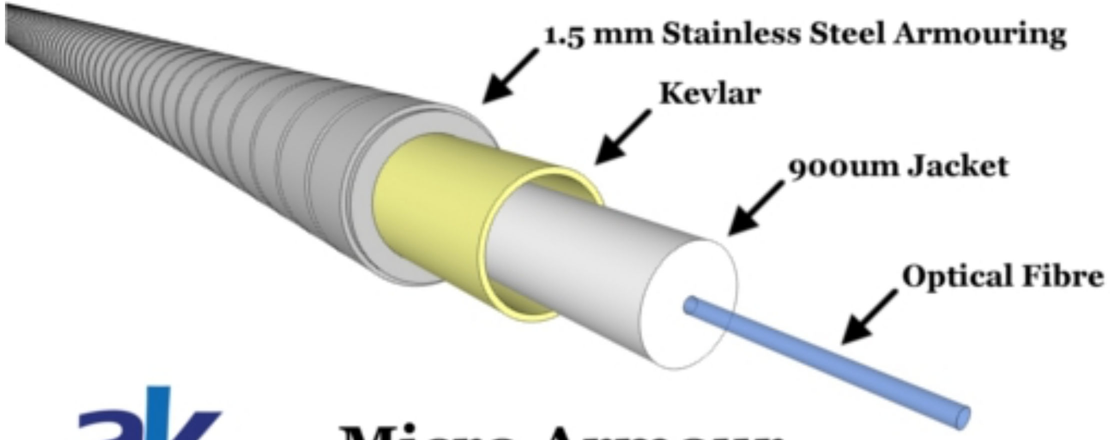
Preferable to independently control 4 degrees of freedom of beam with two mirrors.

Then use a 3-axis fine resoultion stage to move the fibre into the focus of the laser beam

Transport in fibre over >100m:

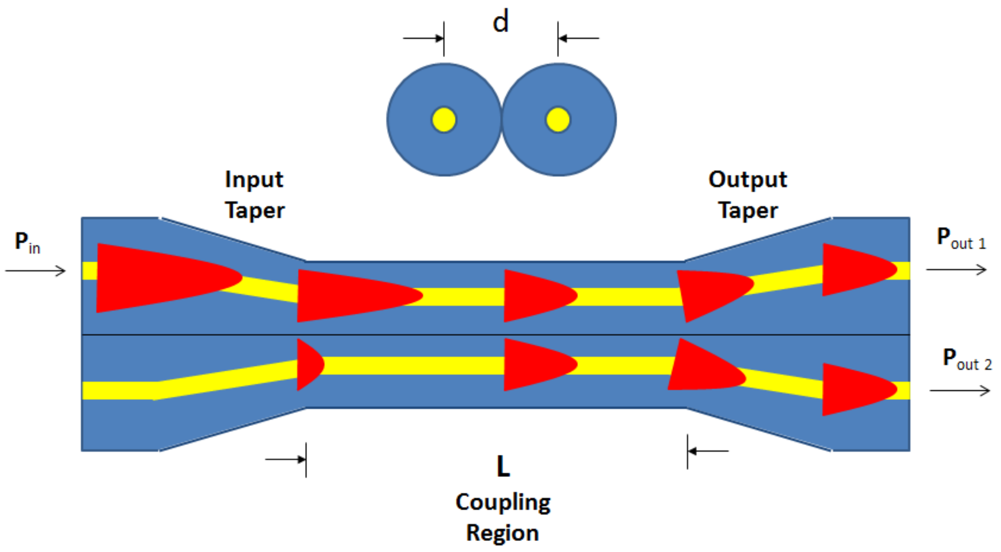
- *Then transport the light >100m in optical fibre*
- *250um diameter bare fibre is extremely delicate: need a ruggedized cable, robust enough for installation in accelerator tunnel.*
- *Satefty interlock in cable to cut power in case of damage.*





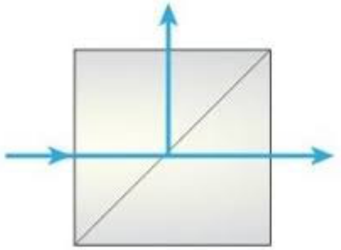
Splitting light between multiple channels

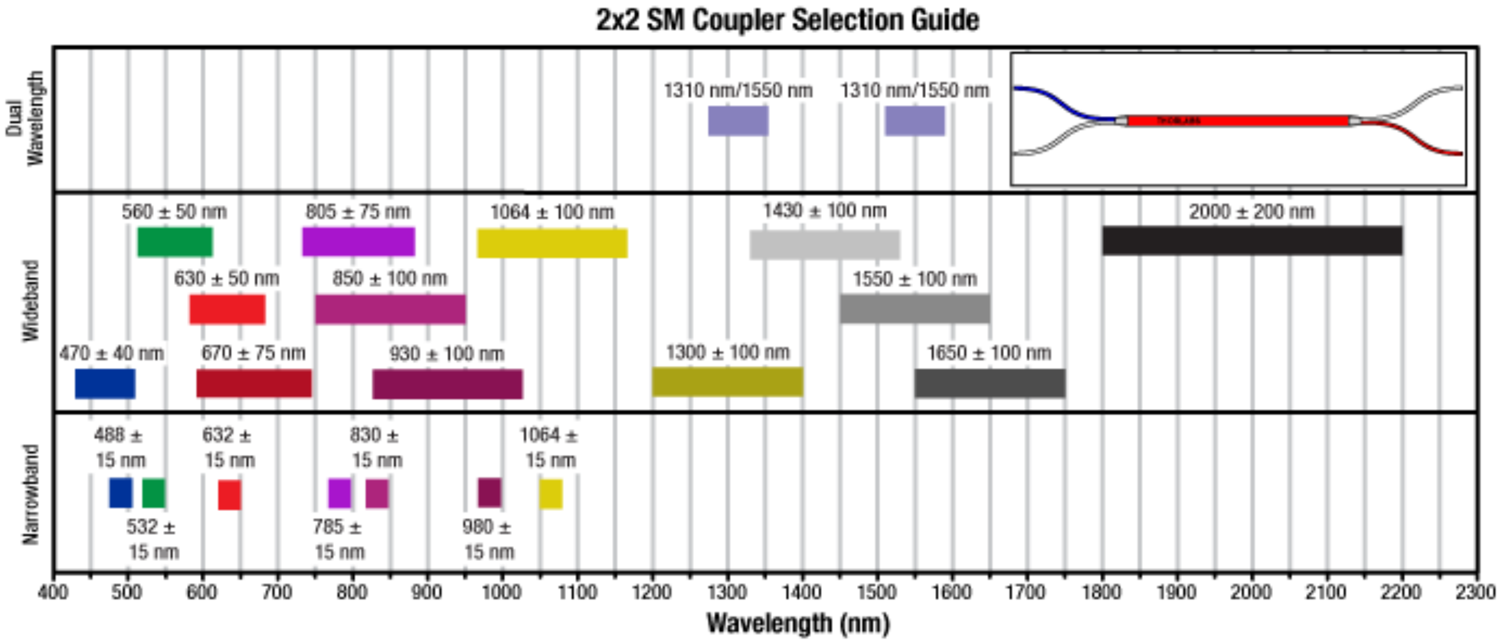
- *Fibre splitters: **fused biconic tapered coupler** :*



Different split ratios available, 50:50, 70:30, 95:5 tap couplers
Fibre types:
Single Mode – e.g. for interferometry
Polarisation Maintaining – e.g. for EO sensitive applications

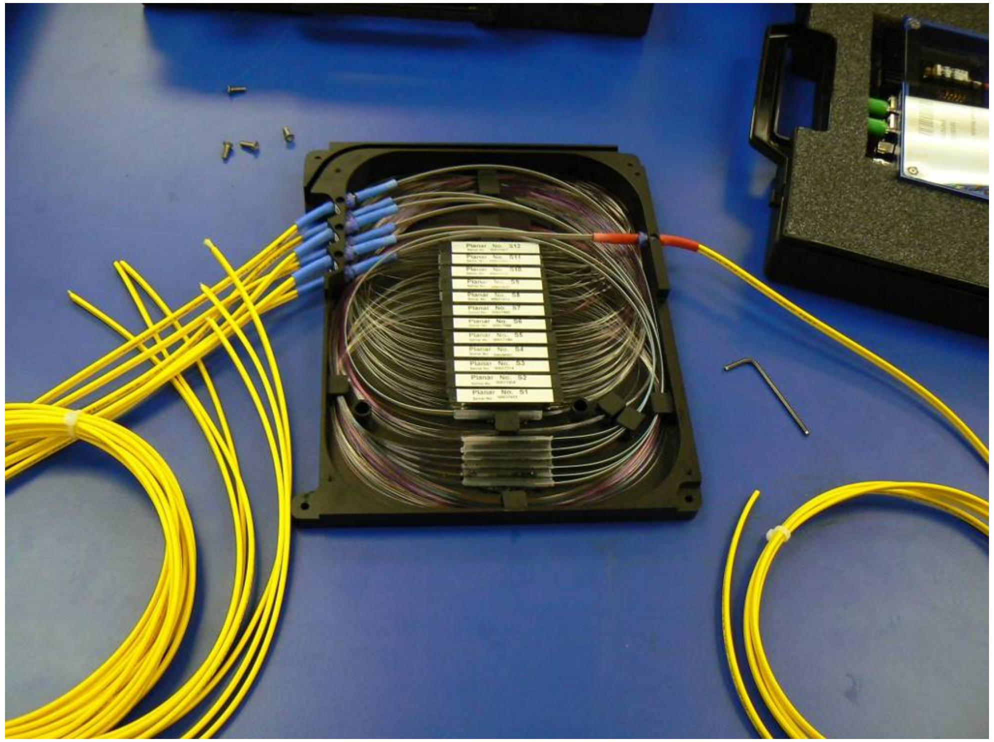
Equivalent optics to beam splitter cube



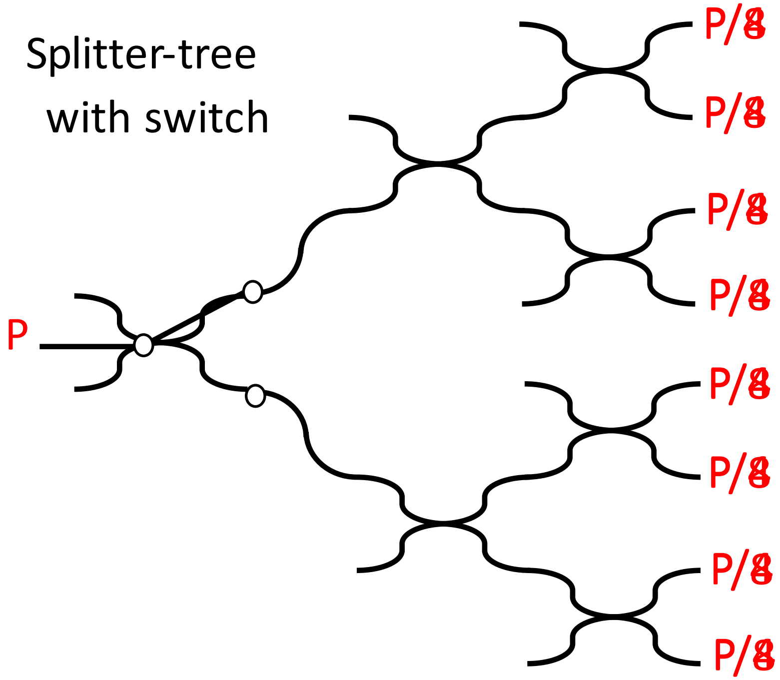


Splitting light between multiple channels

- *Fibre splitters: **fused biconic tapered coupler**, with optical switching*

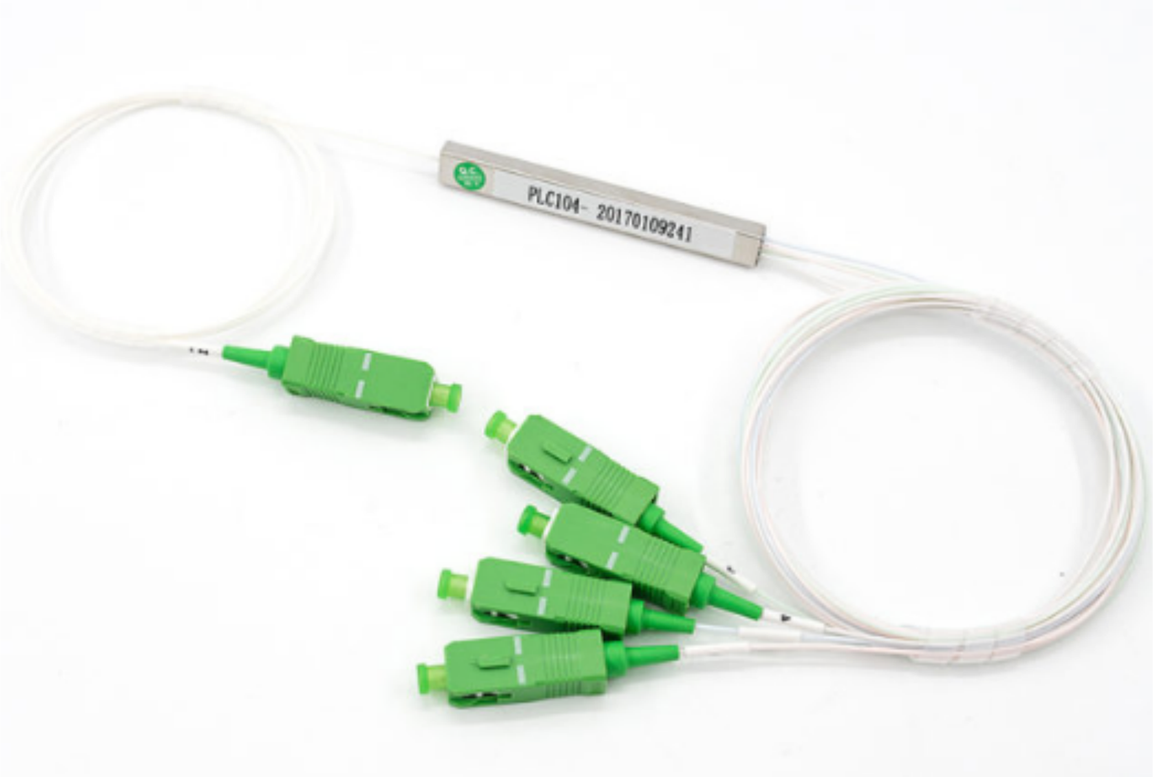


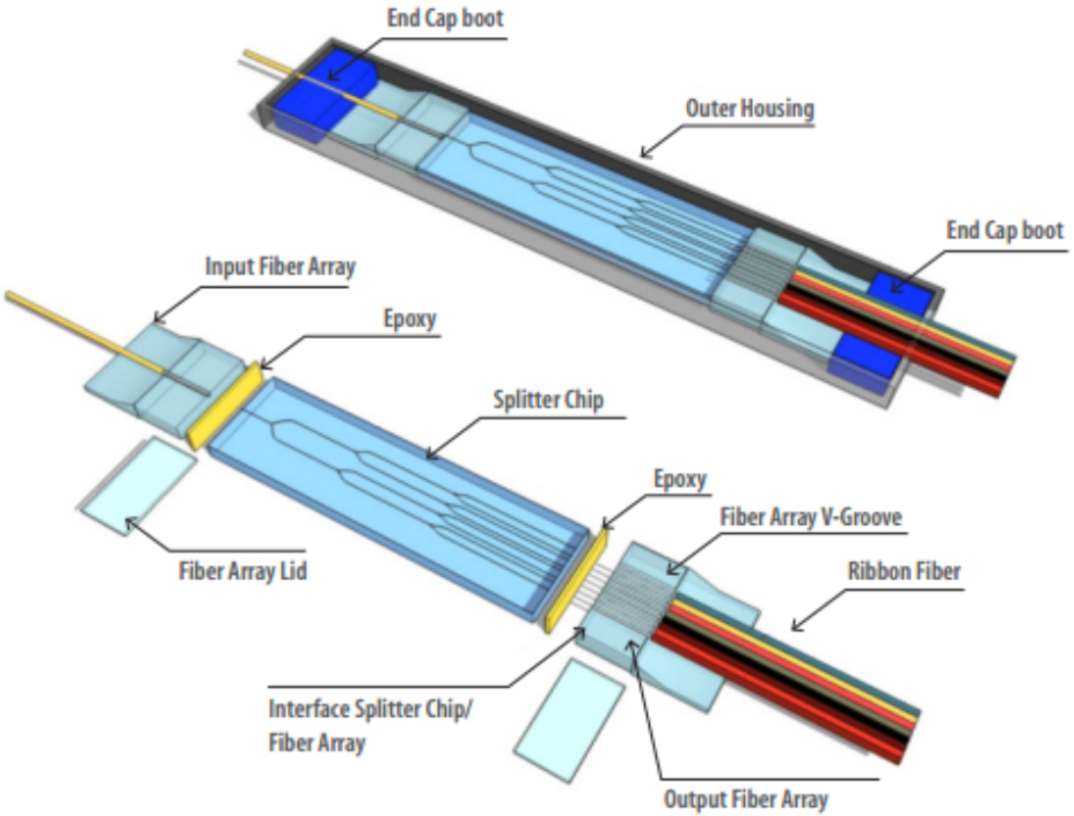
Splitter-tree
with switch



Splitting light between multiple channels

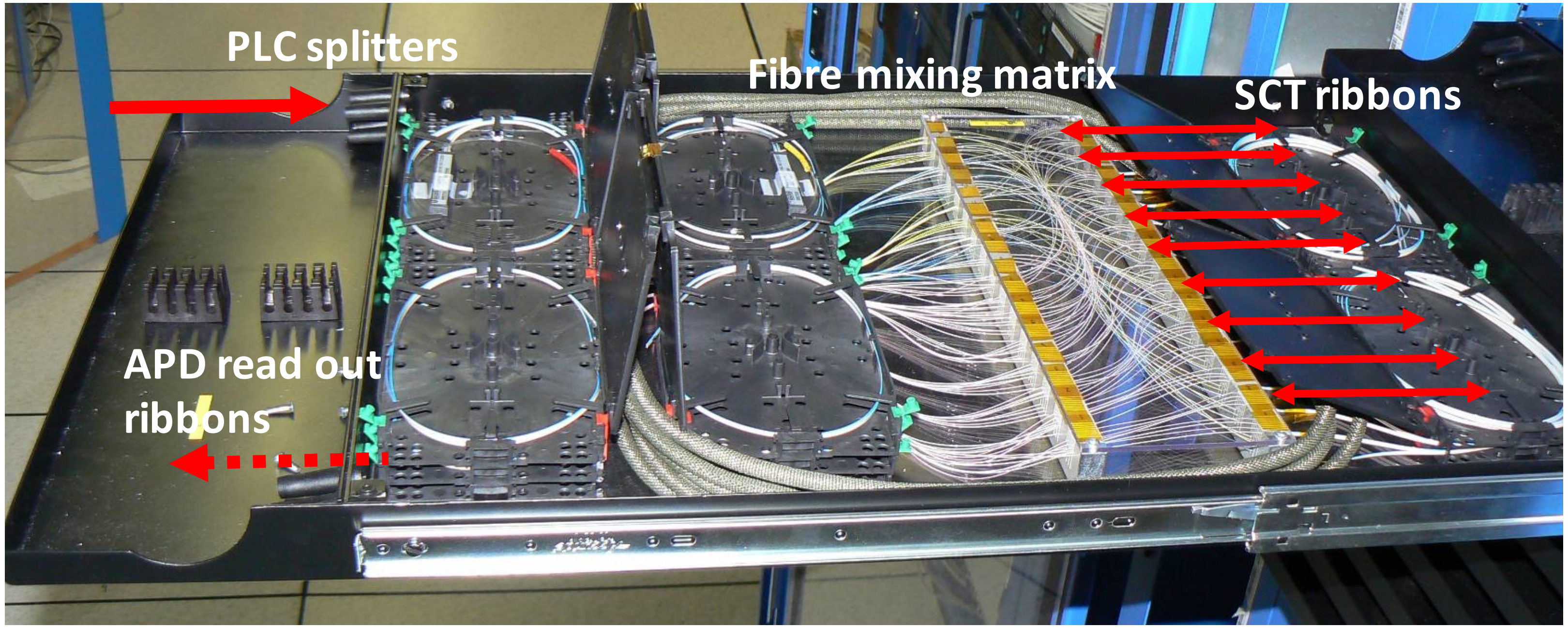
- *Fibre splitters: **or Planar Lightwave Circuit**:*





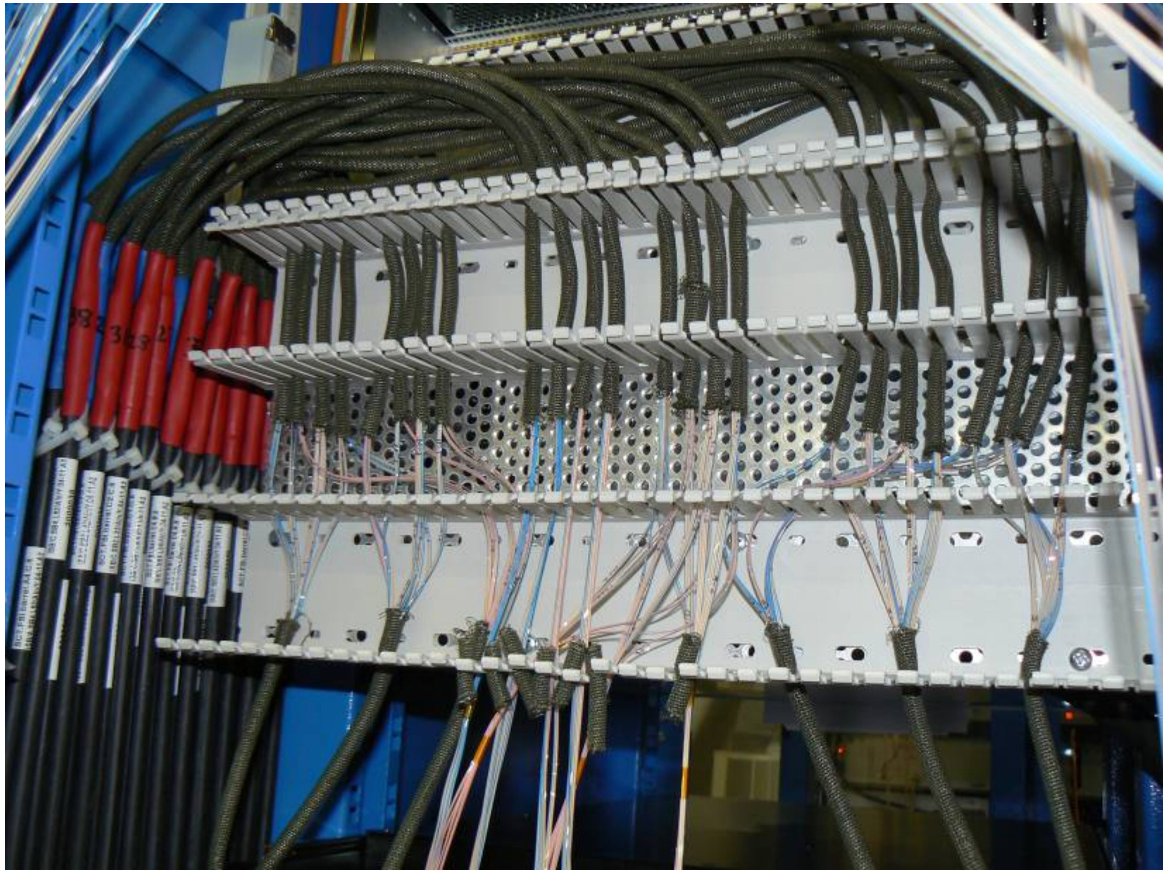
Fibre Splitter Tree and Fibre Management

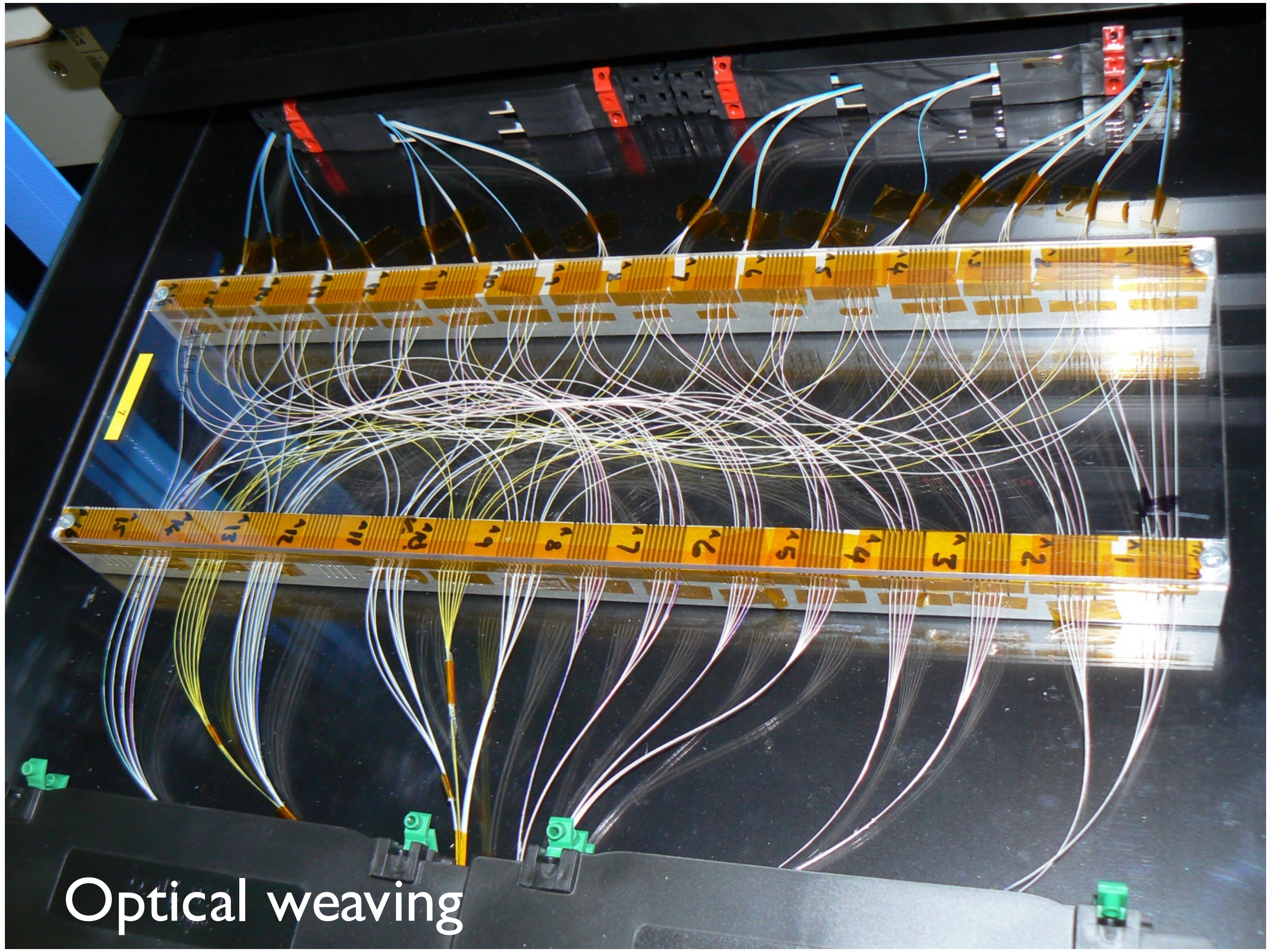
- *Optical fibre splitter tree based on planar lightwave circuits*



Fibre Management System

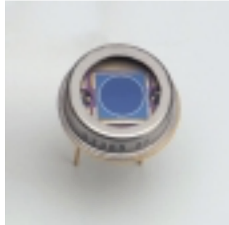
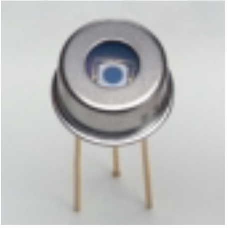
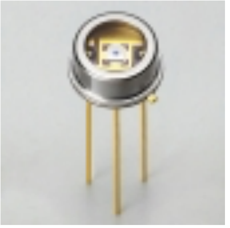
- *842 interferometers > 1684 fibres to manage at the rack!*
- *Fibre ribbons split into bare fibre and individually routed, optical ribbons fusion spliced.*





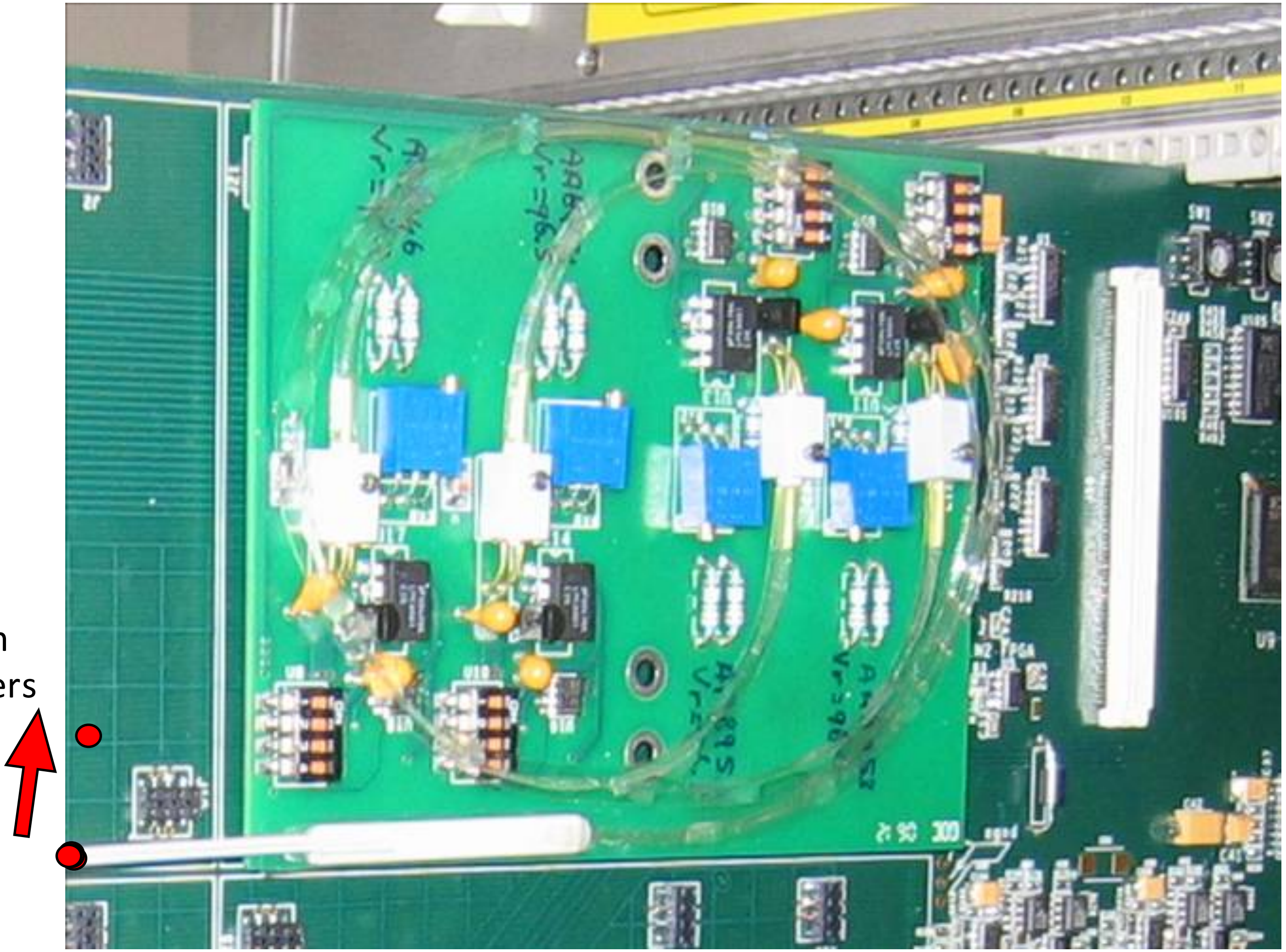
Optical readout challenges

- *Readout of 842 fibres signals*
- *pW signals recorded by Avalanche Photo Diodes (slow signals)*
- *More challenging at accelerators for higher bandwidths, which require smaller sensor size.*

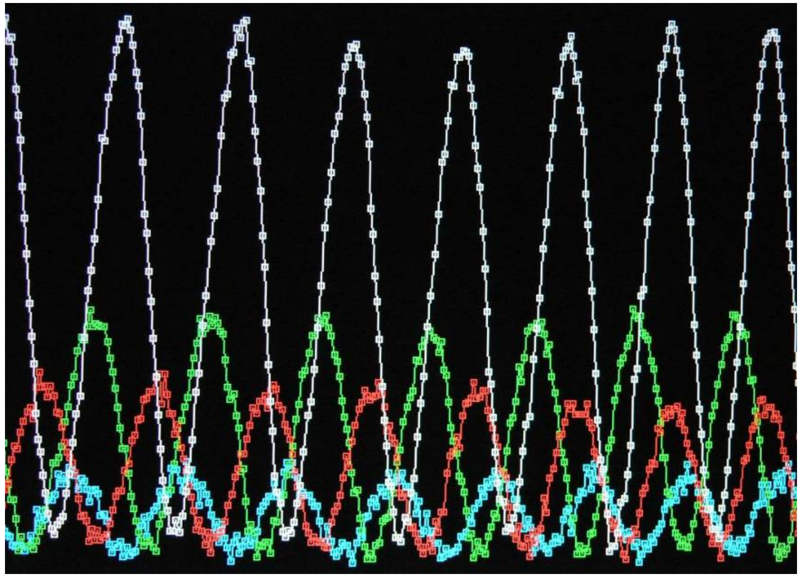




- *This implies very precise alignment of the fibre output with the sensor.*
- *APDs potted to reduce background light reaching sensor.*

Vintage multichannel readout card:



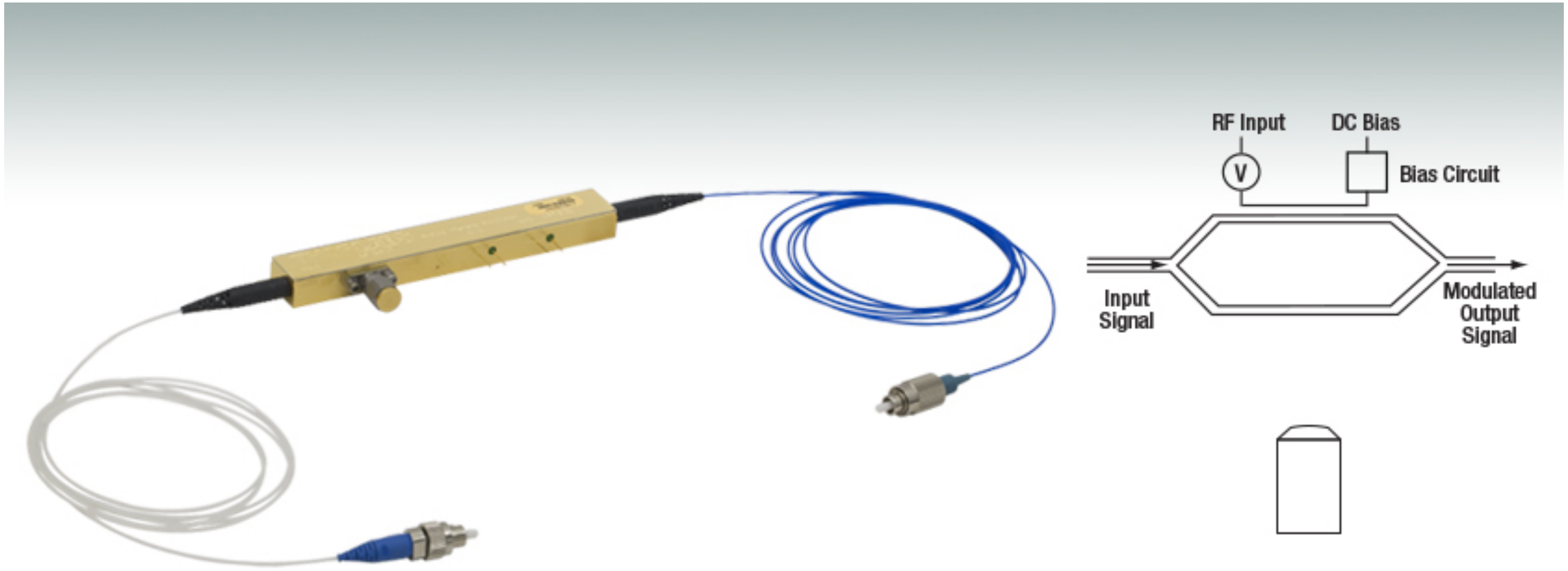
pW signals from
8 interferometers



4 APDs per daughter board read out 8 interferometers.
Whole card reads out 64 interferometers. 16 cards in total.

EO-modulators for high bandwidths signals

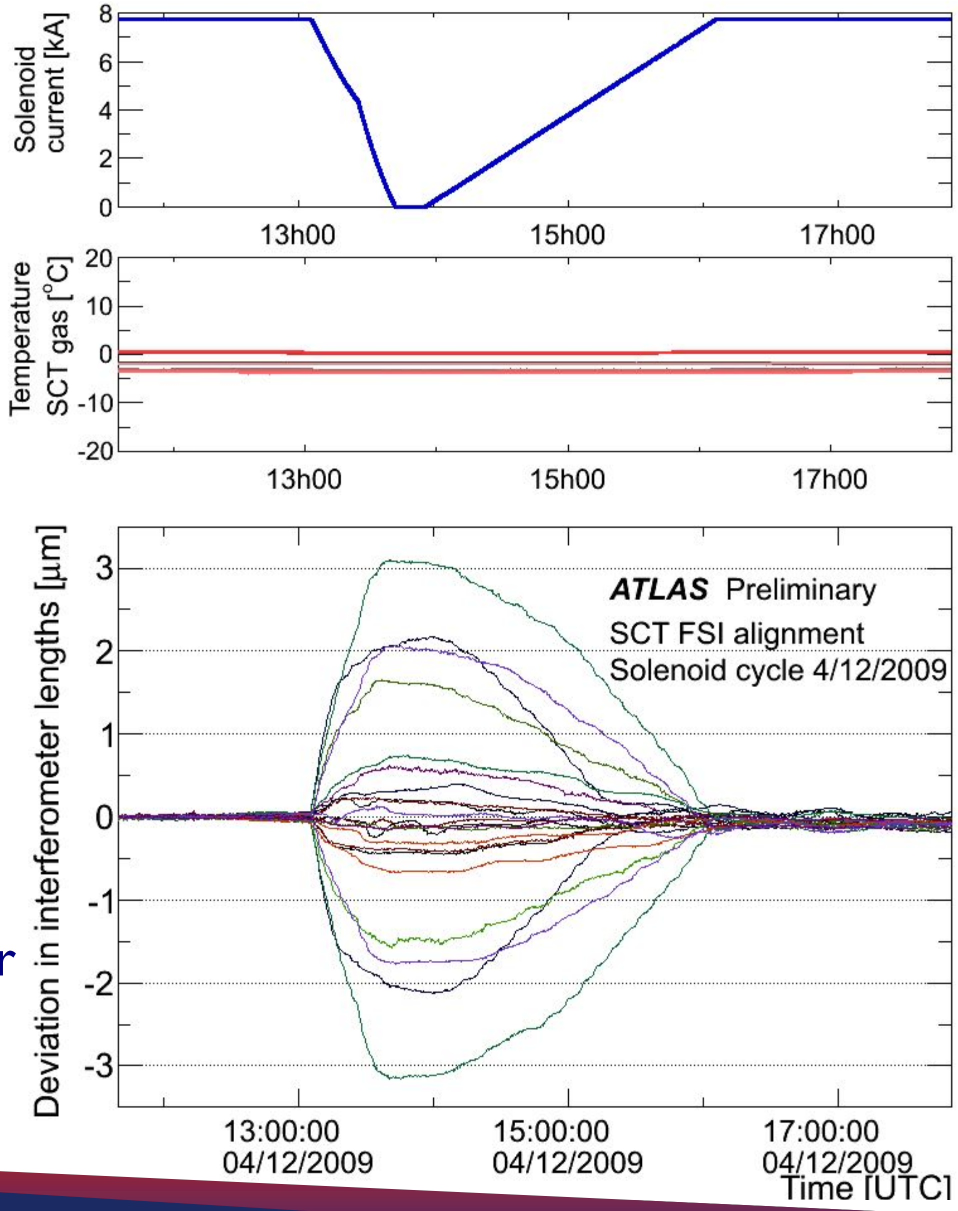
- *Analogue electrical signals can be readout by electro-optic modulators that encode the voltage change into a optical signal:*
- *Enables high bandwidth (to 40GHz) transmission of data from accelerator over >100m in fibre.*
- *Based on an fibre coupled Mach-Zehnder Interferometer in eo-crystal (more next lecture)*



Finally: measurements!

ATLAS FSI measurements of particle tracker distortions

- Developed novel technique to improve sensitivity of laser alignment system.
- Real micron-level movements of the particle tracker can be precisely observed, correlated with e.g: ramps in the solenoid field.
- Remarkable stability otherwise:
  - Before ramp: $\sigma \sim 11$ nanometres.
  - After ramp: interferometer lengths return within $\sigma \sim 49$ nm.
- Demonstrates ultra precise, remote measurements.
- FSI systems also proposed within JAI for linear collider alignment of accelerator chain and final focus magnets.



Summary of 'Lasers: technologies, setups'

- *Lasers enable precise measurements due to the intrinsic properties of light:*
  - *Monochomatic, coherent, highly directional and can be focused to sub-micron scales.*
- *Selection of your laser depends on matching many parameter to meet the requirement of your application:*
  - *Wavelength fixed or tunable, optical pulse energy / CW power, repetition rate, spatial and spectral beam quality, divergence, longitudinal and transverse mode stability, power fluctuations…*
- *When developing beam instrumentation for an accelerator environment must consider many issues:*
  - *Safety for personnel and laser equipment, rate of access*
  - *Beam transport from laser to accelerator - free-space or fibre?*
  - *Radiation tolerance , size of components*
  - *Optical readout technologies*
- *Next time: applications of lasers in beam instrumentation (focus on beam diagnostics).*