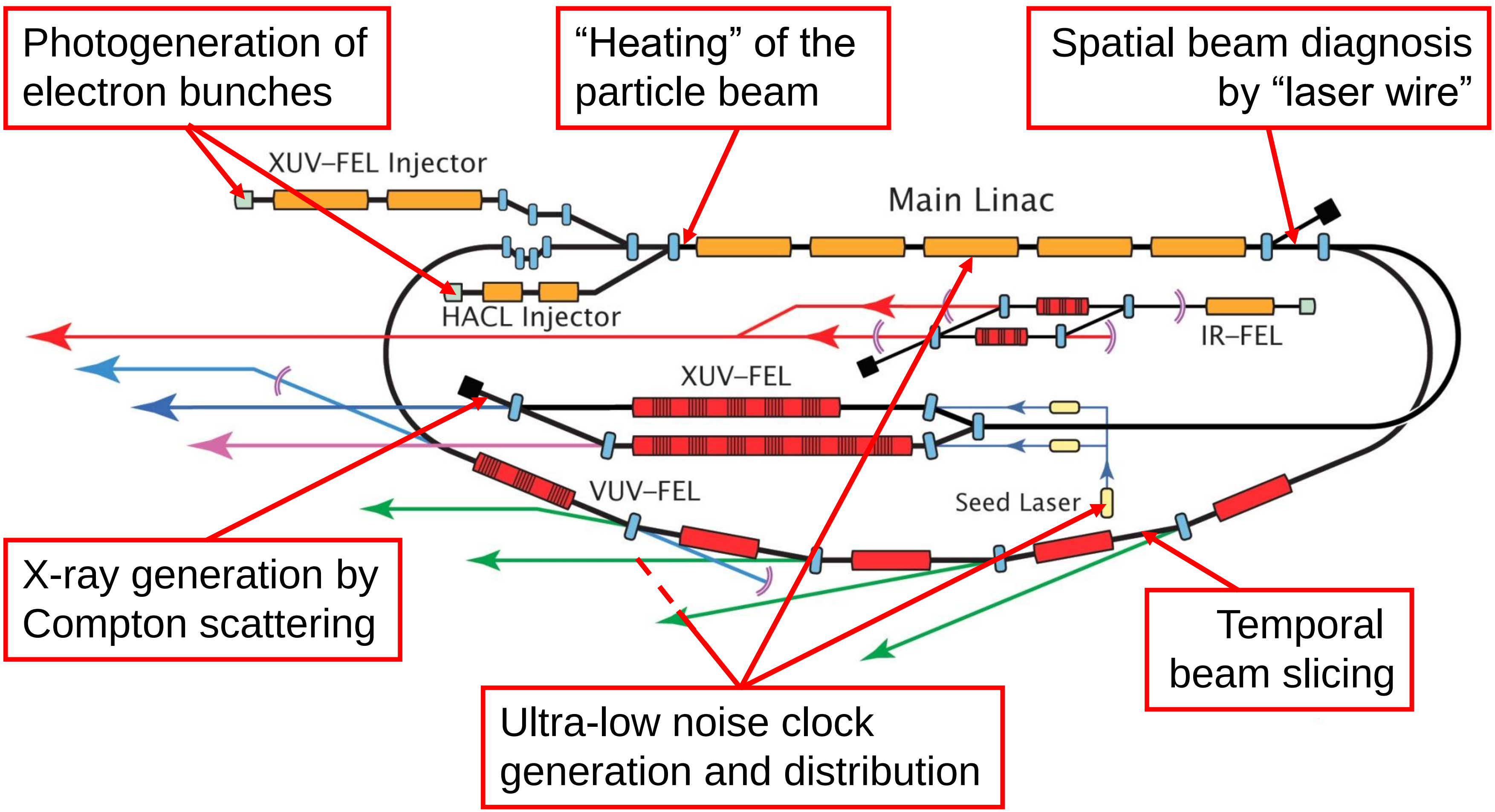
Characterisation of the Laser output

David Walsh

Lasers in Accelerators



What can we measure?

- Energy delivered
  - Average power
  - Pulse energy
- Distribution in space
  - Size
  - Shape
  - Position of beam
- Distribution in time
  - Continuous wave
  - Pulsed/modulated
  - Modelocked pulse characterisation
- Spectral Content
  - Wavelength
  - Bandwidth
  - Phase

Quite a lot!

First things first…

Where is the beam???

Visible laser are… visible.

But, laser safety goggles block the light!

Two options – viewer cards and cameras

Power/Energy

- Many applications are very sensitive to intensity
  e.g. nonlinear optical processes

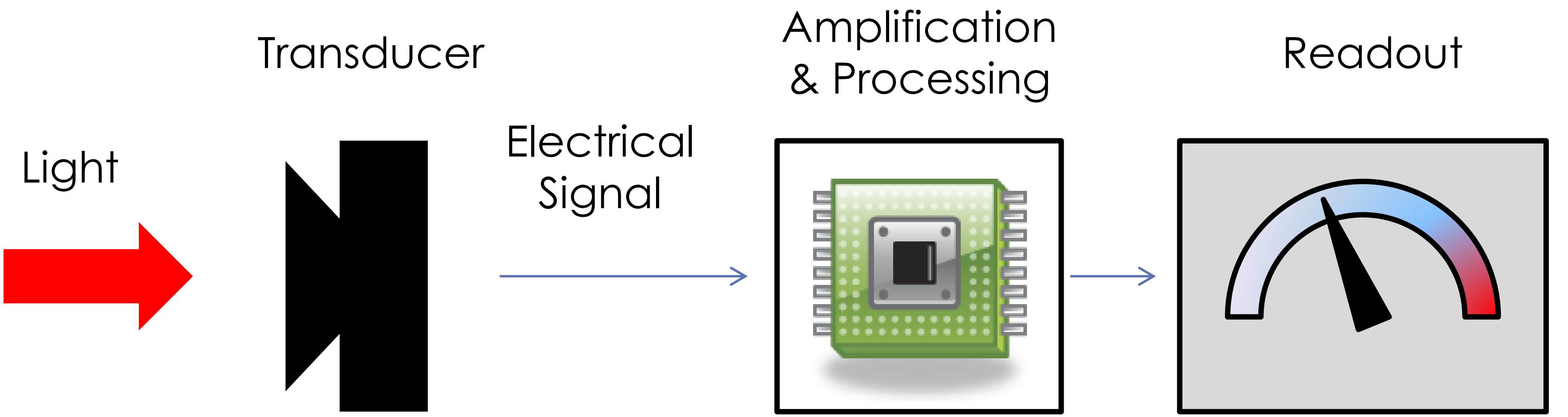
- Laser induced heating can be a problem (or desired!)

- Affects signal to noise ratio in measurements

- There may be a maximum power allowed
  e.g. material damage threshold

- Is it dangerous? – safety glasses etc…

Power Meters



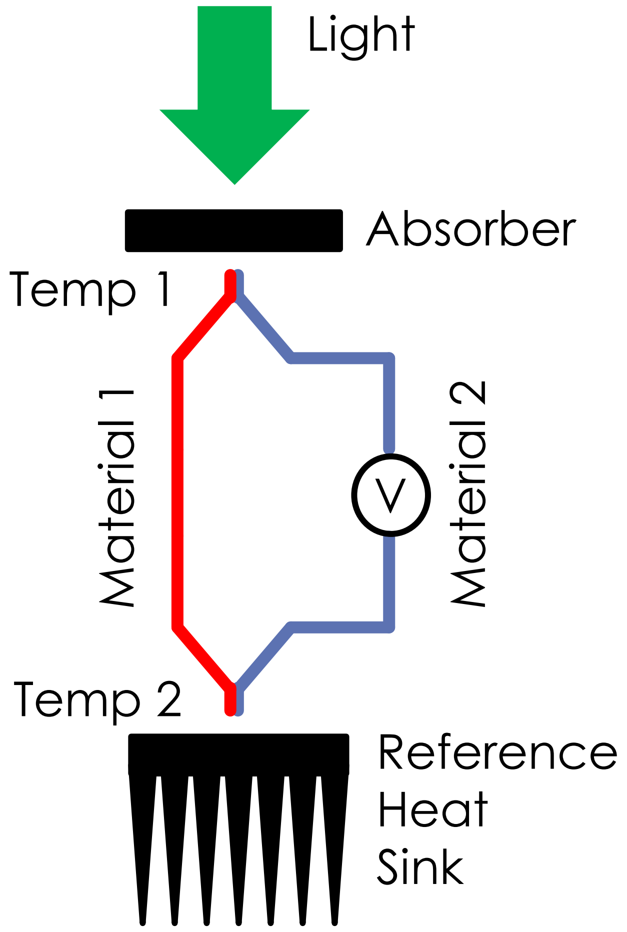
2 main categories of transducer:

Thermal and Photonic

The main 3 types in commercial meters are
Thermopiles, Pyroelectrics, and Photodiodes

Thermopiles

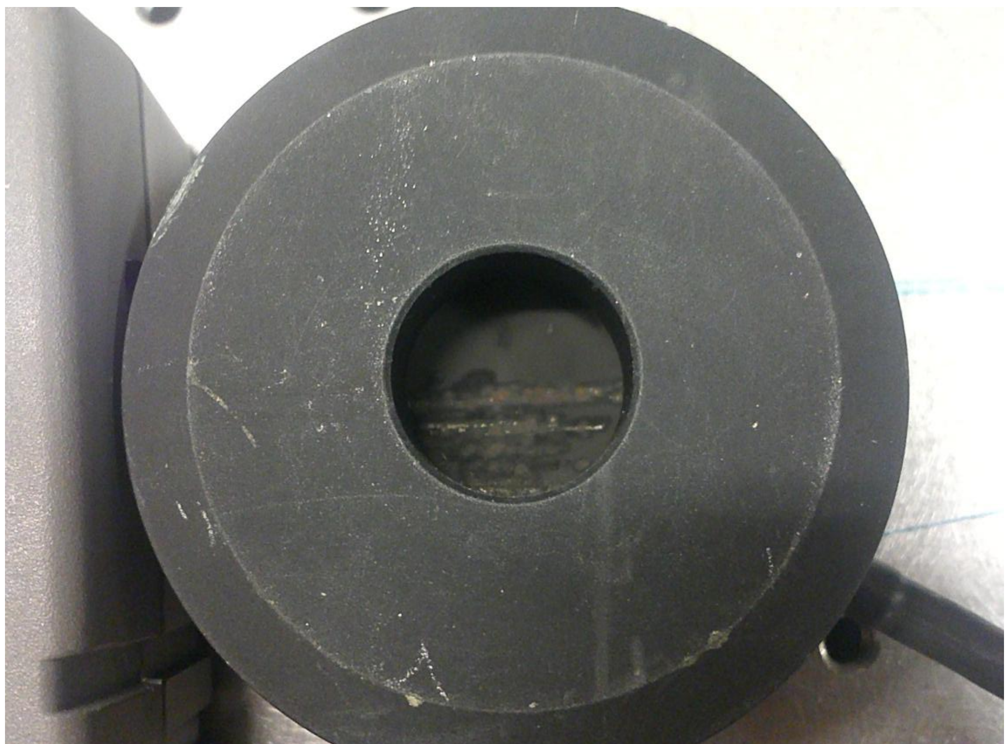
- Seebeck effect
  - Differential diffusion of electrons due to heat
- Multiple thermocouples
- Linear response
- Flat response over wide range
- Scalable - few mW to many kW
- Absorbing surface can be large
- Slow response time (seconds)
- Very common



A word of warning

You can still damage your 10W detector head with a beam of much lower average power!

Especially if the laser is pulsed!

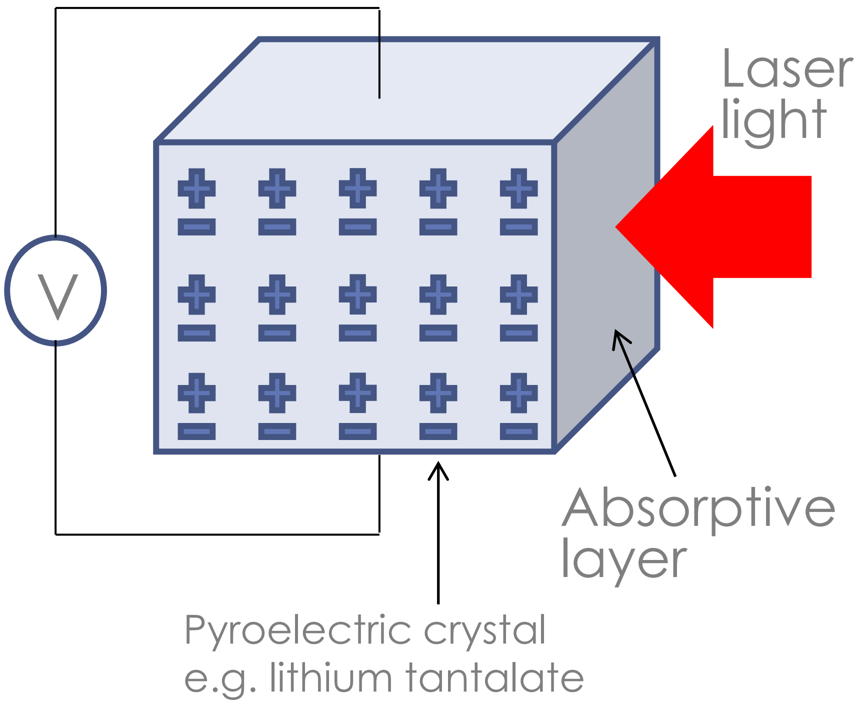


Use the appropriate specification head and expand the beam.

Pyroelectrics

- The unit cell has an electrical polarisation
- On heating the unit cell deforms, changing the electrical polarisation
- This yields a detectable voltage across the crystal - which then leaks away due to charge flow

- Faster than thermopiles (few ms)
- Needs a modulated source
- Spectrally flat response
- Pyroelectric response accompanied by piezoelectric response – sensitivity to vibrations

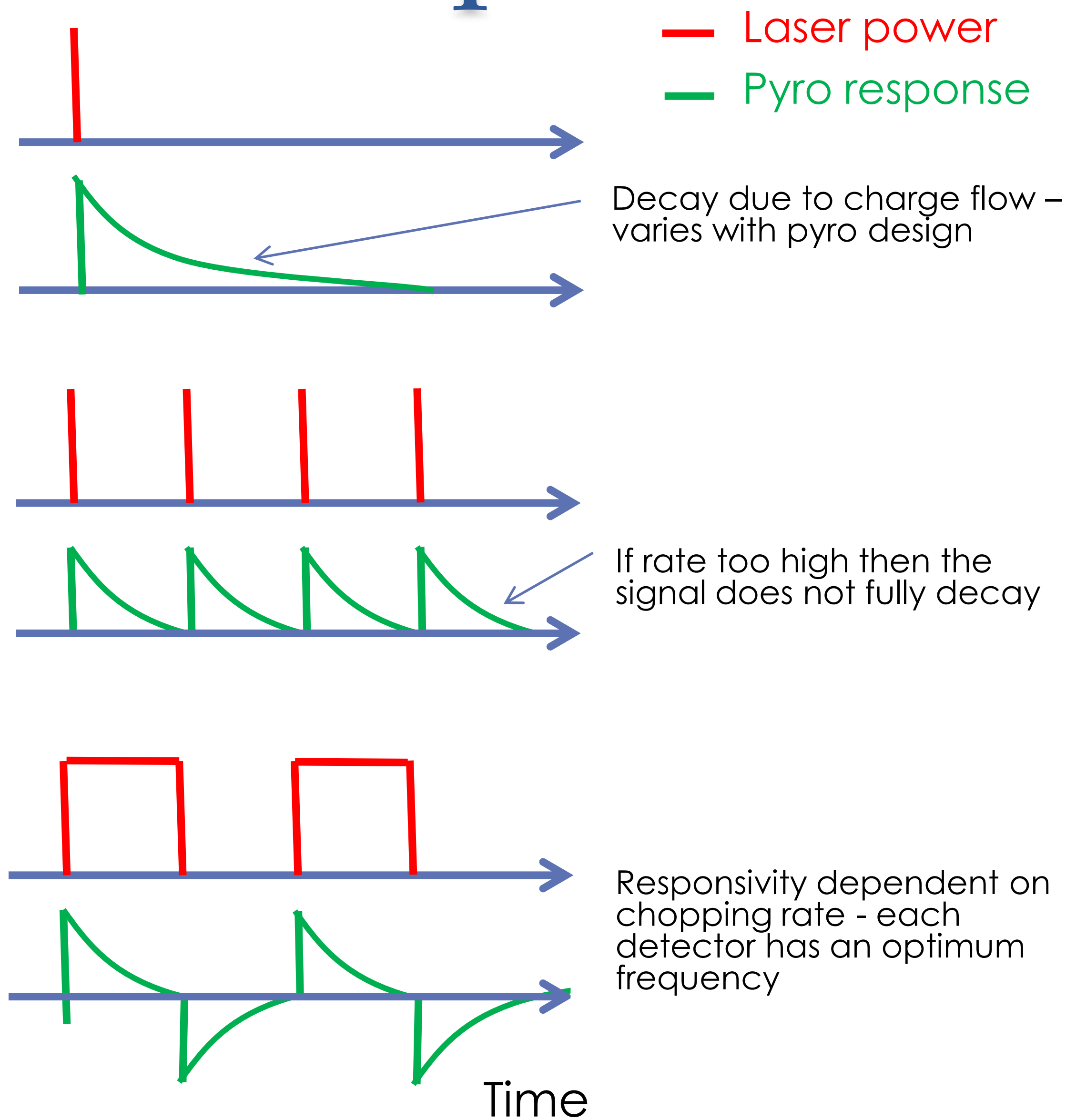


Temporal Response

Response to a "short-pulse"

Response to a "short-pulse" train

Response to a chopped CW beam



Photodiodes

- "Quantum" detectors

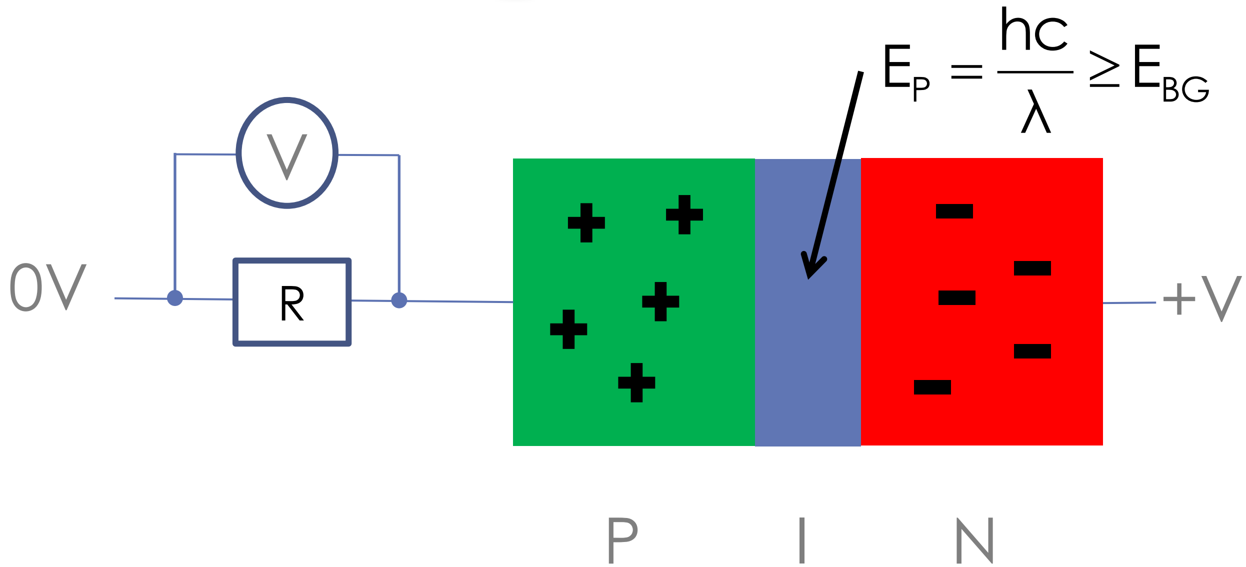
- A photon(s) absorbed in a semiconductor generates an electron-hole pair(s)

  $(E_{photon} > E_{bandgap})$

- This can then be detected as either
  - A reduction in the resistance of the semiconductor
  - A build-up of voltage across a PN/PIN diode
  - Or current flow through a reverse biased PN/PIN diode

- The reverse biased PIN photodiode configuration has a fast, linear response

PIN photodiodes

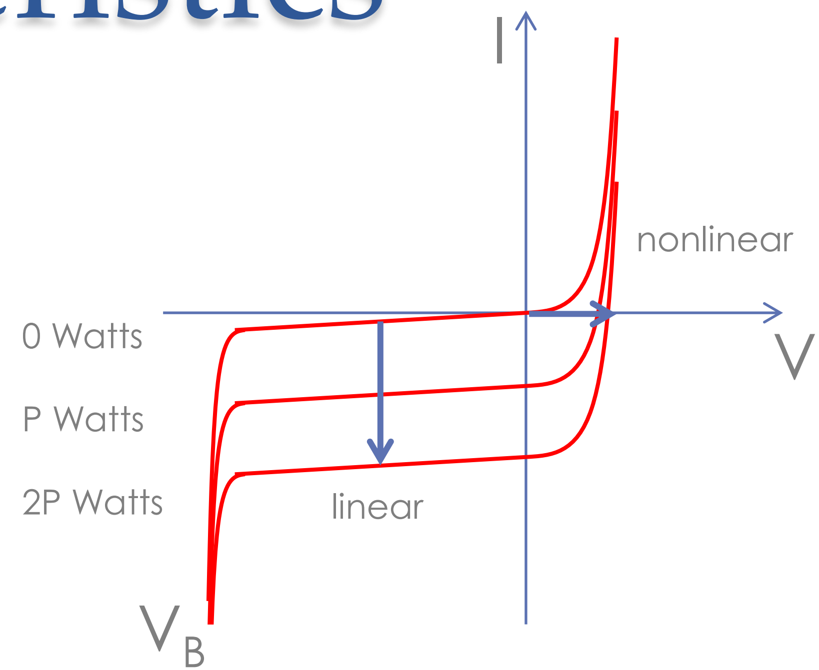


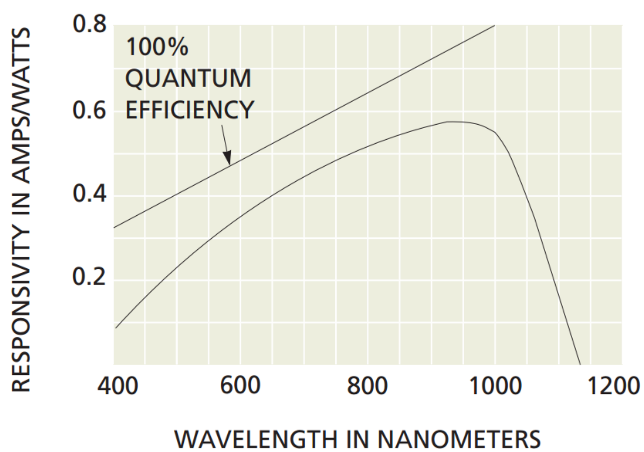
- Under reverse bias, in the dark, little or no current flows due to a "depletion region"
- A photon hits depletion region, generates an e-h pair
- Bias field sweeps electron to N doped side, and hole to P doped side
    - Equivalent to one charge carrier flowing in circuit
- Current flow is detected as a voltage across load resistor R

Photodiode Characteristics

$$I = -\frac{\eta q P}{h\nu} + I_0\left(e^{qV/k_B T} - 1\right)$$

(efficiency)*(charge)*(no.photons)





Ref: CVI Melles Griot Si PD datasheet

- Spectrally varying responsivity (Amps/Watt)
- Different materials for different wavelength ranges
  - Cooling needed for longer wavelengths
- Sensitive but easily saturated
  - Attenuation needed for > few mW

Spatial Profile

How the power/energy of the beam is distributed in space orthogonally to the propagation direction.

Importance

- The size of the beam allows us to
  - Calculate optical intensity available for nonlinear optics processes
  - Prevent optically induced damage
  - Ensure beam optics will not clip and aberate the beam
- The profile can highlight departures from Gaussian beam shape
  - "Hotspots" can seed damage
  - Much of the modelling of beam transport, shaping, and "mode-matching" is based on Gaussian beams

Gaussian Beams

- A Gaussian beam has a circular intensity profile of the form

$$\underbrace{I(r,z)=\frac{P}{\frac{1}{2}\pi w(z)^2}}_{\substack{\text{Normalisation of intensity}\\ \text{(Power/Area)}}}\;\underbrace{e^{-2\frac{r^2}{w(z)^2}}}_{\substack{\text{Gaussian expression with intensity}\\ \text{falling to } e^{-2} \text{ of the peak at } r = w(z)}}$$

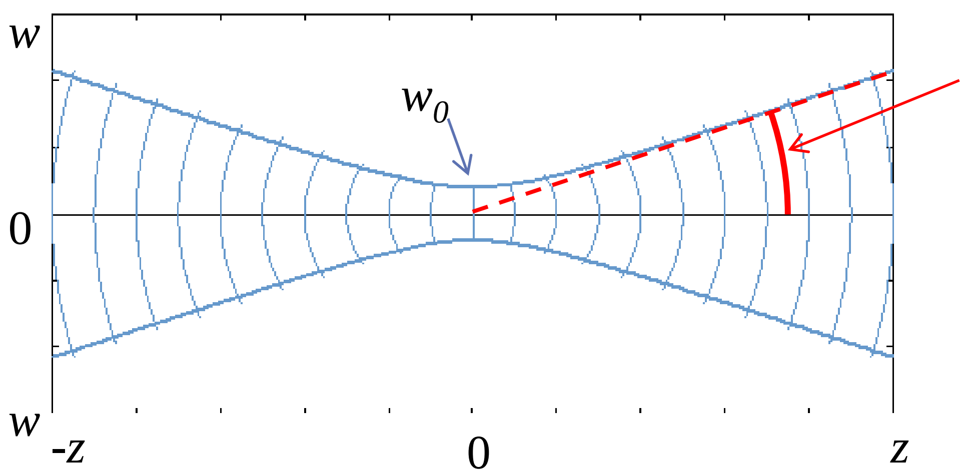
- When a Gaussian beam propagates it remains Gaussian
- They also remain Gaussian on passing through simple optical elements (lenses etc…)
  - This is not the case with most beam profiles, consider diffraction patterns from slits and apertures for example
  - This self-consistency allows such a beam to experience efficient gain over many round trips of a laser cavity

Beam Propagation

- Under the paraxial approximation the beam size *w(z)*, and radius of curvature *R(z)* of the phase front, are described along the propagation direction *z* by

$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2} \qquad R(z) = z\left(1+\left(\frac{\pi w^2}{\lambda z}\right)^2\right)$$

Beam "waist"



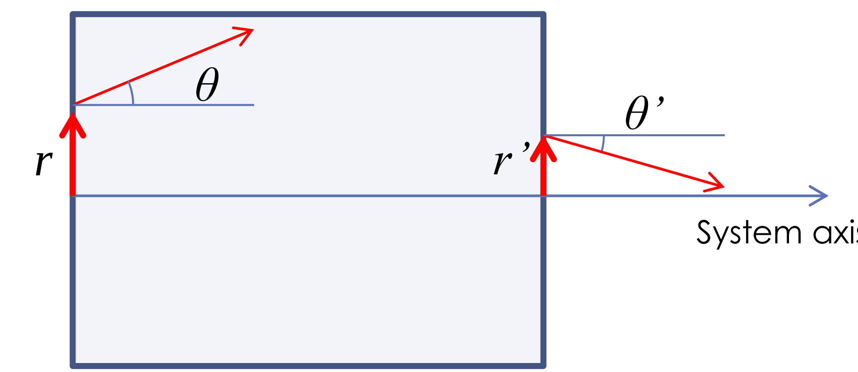
Far-field diffraction angle $\theta = \dfrac{\lambda}{\pi w_0}$

Rayleigh Range $z_R = \dfrac{\pi w_0^2}{\lambda}$

(Distance at which the area of beam has doubled)

ABCD Matricies

- In ray optics it is possible to model an optical element as a 2x2 matrix
- The effect of the element on the ray can be found by matrix multiplication
- Multiple elements can be modelled by multiplying their matrices together



$$\mathrm{R}=\begin{pmatrix} r \\ \theta \end{pmatrix} \qquad \begin{pmatrix} A & B \\ C & D \end{pmatrix} \qquad \mathrm{R}'=\begin{pmatrix} r' \\ \theta' \end{pmatrix}$$

$$\mathrm{R}'=\begin{pmatrix} r' \\ \theta' \end{pmatrix}=\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} r \\ \theta \end{pmatrix}$$

Some examples:

Freespace of length d $=\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$

lens of focal length f $=\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$

Complex Beam Parameter

- The ABCD method can be extended to Gaussian beams with the complex beam radius, *q(z)*

$$\frac{1}{q(z)} = \frac{1}{R(z)} - i\frac{\lambda}{\pi w(z)^2}$$

- After finding the optical ABCD matrix as before the complex radius of curvature is transformed in the following way

$$q'(z) = \frac{Aq(z)+B}{Cq(z)+D}$$

- So, characterisation of the beam allows us to predict its form elsewhere

P. Bélanger, "Beam propagation and the ABCD ray matrices," Opt. Lett. 16, 196-198 (1991).

M^2 Factor

The ideal beam would be a perfect Gaussian, but in reality this never occurs.

Real beams have some level of abberation due to aperturing, thermal lensing and misallignment of optics, for example.

There are also higher order, self-consistant ,modes called the Hermite- and Lageurre-Gaussian modes, that can be produced by a laser.

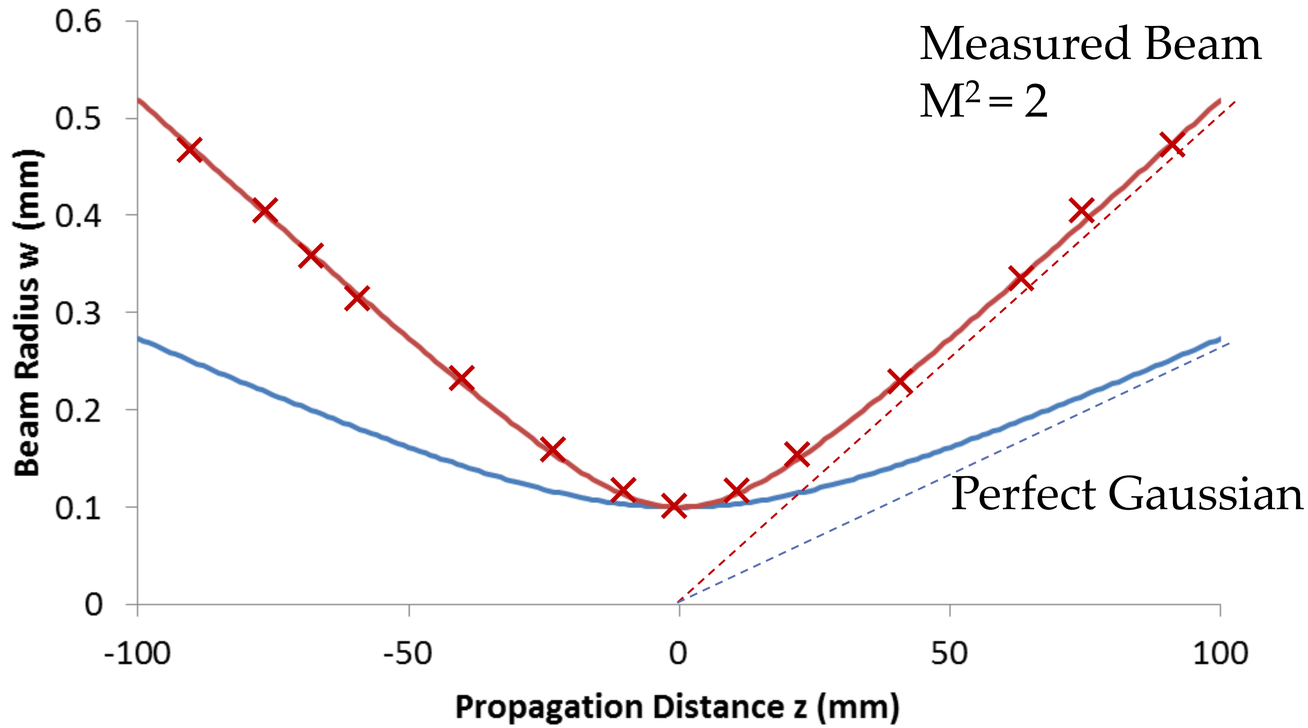
Therefor a real beam is always larger than suggested from modelling a perfect Gaussian beam.

M^2 Factor

- We can adjust the model of a Gaussian beam to take this into account by including the "M^2 factor"

$$w(z) = w_0 \sqrt{1 + \left(M^2 \frac{\lambda z}{\pi w_0^2} \right)^2}$$

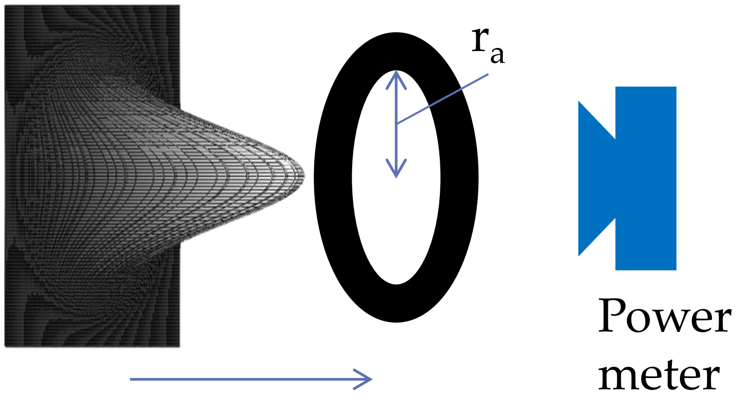
$$\theta = \frac{M^2 \lambda}{\pi w_0}$$



- It is essential to measure the beam waist and the far field diffraction angle accurately

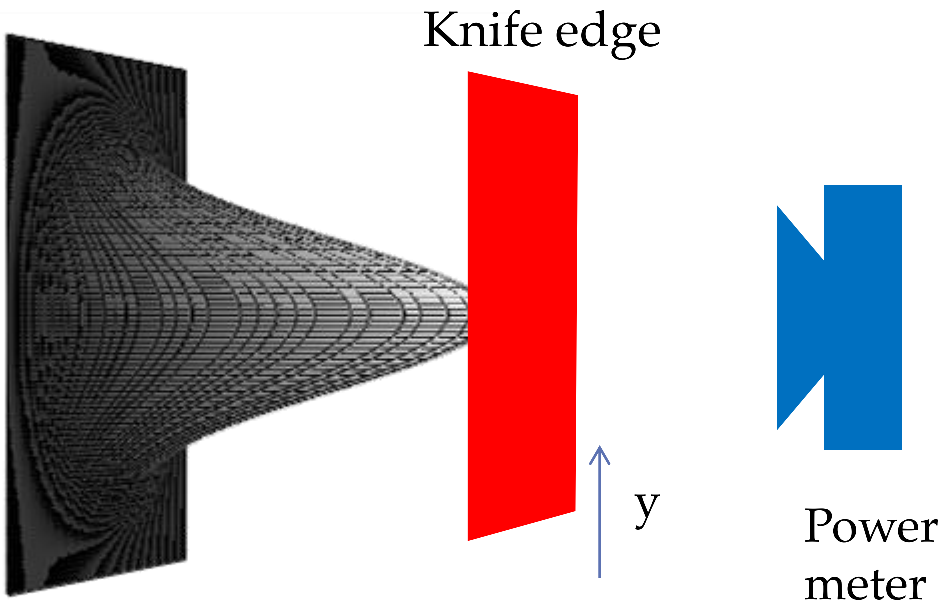
Waist Measurement

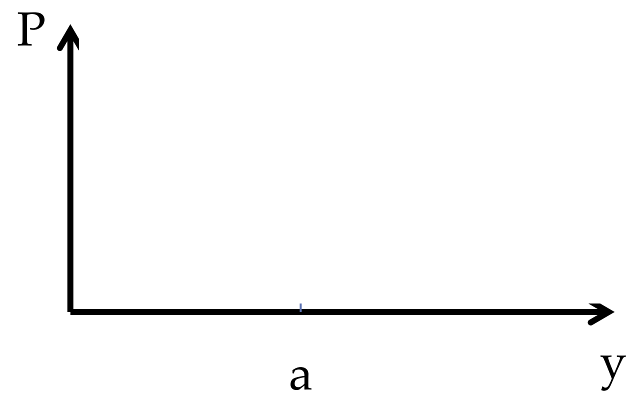
- Burn spots, photographic film, by eye
  - Nonlinear and inaccurate
- Transmission through an aperture, or D86 method
  - Find aperture radius that transmitts 86% of the beam
  - Corresponds to e^{-2} radius, for a Gaussian beam



- Assumes the beam is Gaussian and circularly symmetric

Scanned Knife Edge





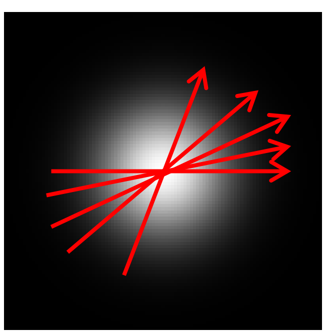
$$\int_0^a I(y)dy$$

- Yields the integrated power across the beam up to the knife edge
- Can compute the Gaussian radius that fits the profile
- Can scan in X and Y directions

Scanned Knife Edges

- Commercial systems typically use multiple knife edges at varying angles

Movement – typically a spinning disc or drum



- Using computed tomography techniques detailed beam profile can be recovered
- Profiles retrieved at a few Hz
- Can be used on small beams
- Not useful for pulsed lasers (spikey data)

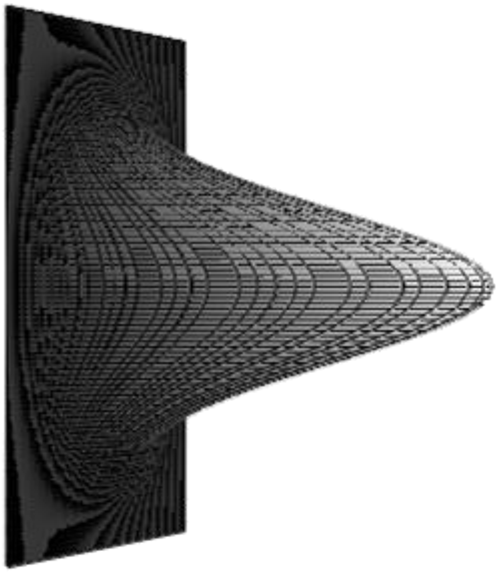
Scanned Aperture

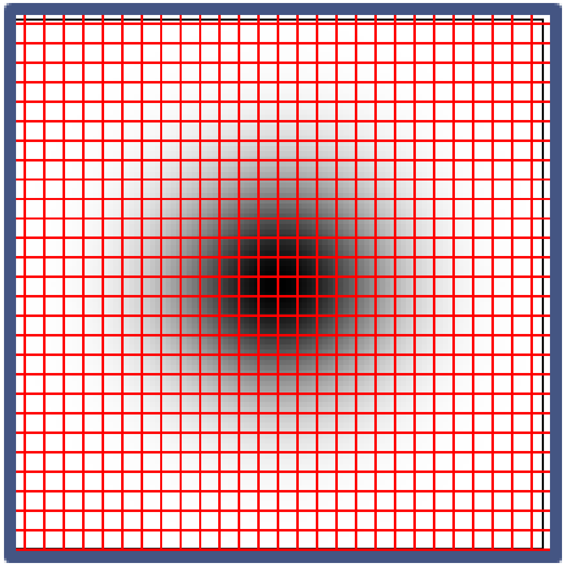
- Instead of using a knife edge, use and aperture and raster it across the beam
- Builds up an accurate and detailed map of the spatial profile
- Takes time!

- Instead of scanning an aperture, we could use a small detector
- Or a 2d array of detectors and get all the data at once!

e.g. CCD and pyroelectric cameras

CCD Beam Profilers



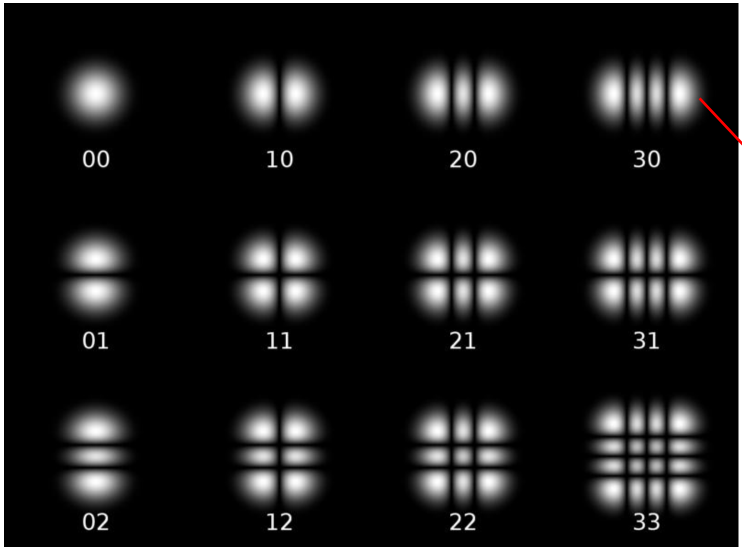


Aliasing

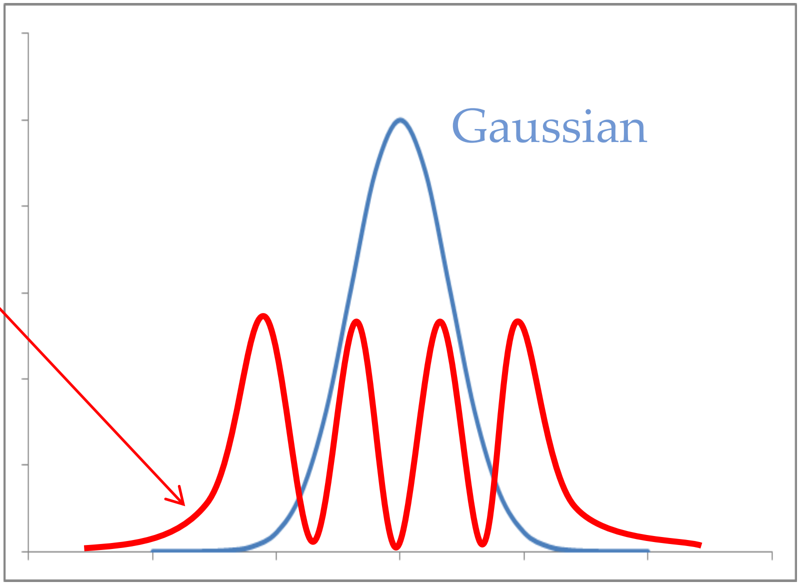
- CCDs are very sensitive
  - Need to heavily attenuate the beam
  - Great care must be taken to not distort the beam with attenuators
- Pixels are of finite size (~few microns)
  - Limits size of waist (focal length of lens) that can be measured
- Whole profile in one measurement
  - Good for pulsed lasers
  - Or beams that change rapidly

Complex Beams

- CCDs allow accurate measurements of complex beam profiles, such as HG and LG modes
- But how can these complex beams be given a "Gaussian" beam radius?



Hermite Gaussian Modes



Downloaded from wikipedia
DrBob at en.wikipedia

"Second Moment" Analysis

- Instead of fitting a Gaussian profile, instead look at the statistical distribution of power
- The standard deviation of the power distribution in the x direction (where x=y=0 at the centre of the beam) is

$$\sigma_x = \sqrt{\frac{\int (x)^2 I(x,y)dxdy}{\int I(x,y)dxdy}}$$

- Beam waist is then defined as $2\sigma_x$
  - Note that for a Gaussian beam, the e^{-2} point is at 2σ
- It can be shown that this waist definition can be used for any arbitrary beam (A. Siegman's book, "Lasers")

ISO Standard 11146, "Lasers and laser-related equipment – Test methods for laser beam widths, divergence angles and beam propagation ratios" (2005)

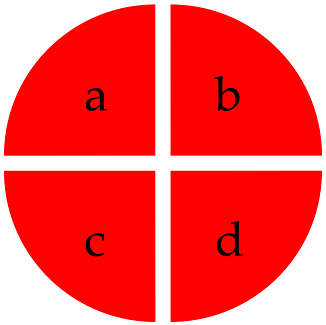
Second Moment Considerations

Being able to use the idea of an embedded Gaussian for an arbitrary beam is very powerful, however

- Calculation is not trivial, computer code is generally necessary
- Waist is highly sensitive to signal further from the axis where the intensity is low
    - Background signal needs to be removed carefully
- The waist and M2 calculated in this way are still not the full story
    - On axis power

Other Parameters

- Beam center
  - Can use the profiler as an allignment tool that is much more accurate than pinholes
- Pointing Stability
  - Drift of the beam over time can be quantified and monitored
  - Useful for long beam transport paths



Quadrant photodiodes offer faster position sensing

Horizontal position ~ (a+c) - (b+d)
Vertical position ~ (a+b) - (c+d)

Spectral Content

Importance

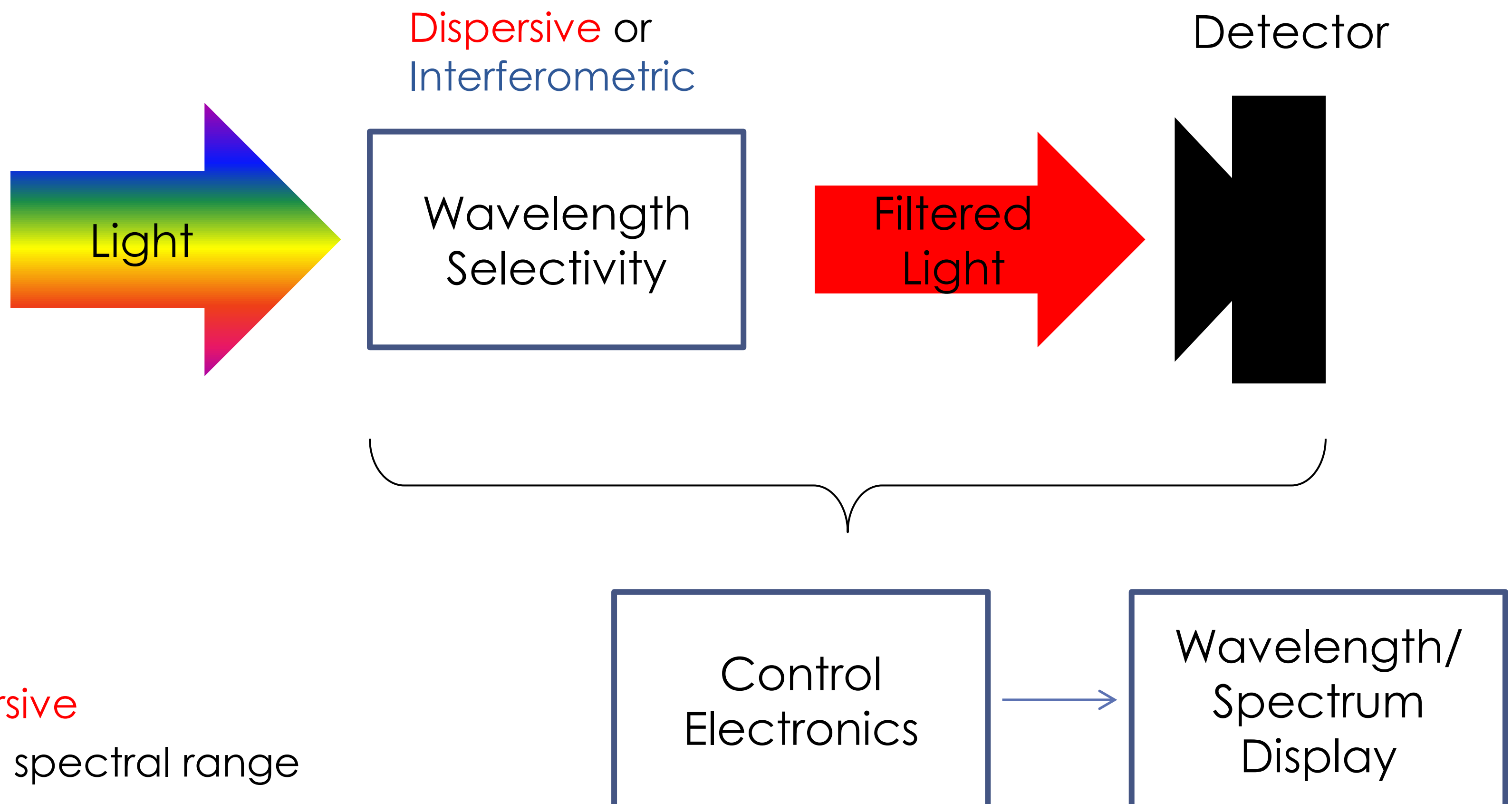
- Need to know the wavelength for beam propagation!
- Wavelength and spectrum corresponds to photon energy distribution
  - Translates into electron energy distribution at photocathode

$$KE = h\nu - \varphi$$

- Spectroscopy
- Phasematching in Nonlinear Optics
- The spectrum is intimately linked to pulse temporal profile through the Fourier transform

Spectrometers

Schematic layout



Dispersive

Broad spectral range

Interferometric

(Extremely) High resolution

Dispersive Methods

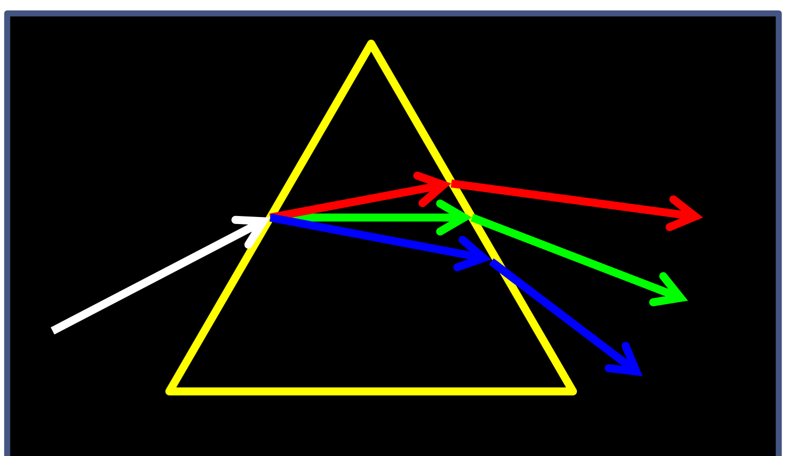
There are two primary techniques for obtaining chromatic dispersion

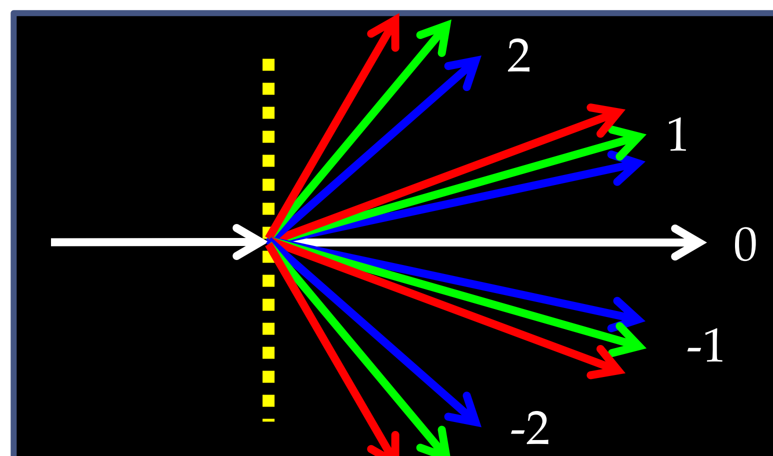
Prisms

- Material dispersion – n(λ)
- Depends on wavelength
- As wavelength gets shorter, dispersion typically increases

Gratings

- Diffraction and interference based
- Constant with wavelength
- Hard to make gratings for very short wavelengths





Grating Dispersion

By considering the path length difference, the condition for constructive interference can be derived

$$m\lambda = d\sin\theta + \mathrm{d}\sin\phi$$

m is the "diffraction order"

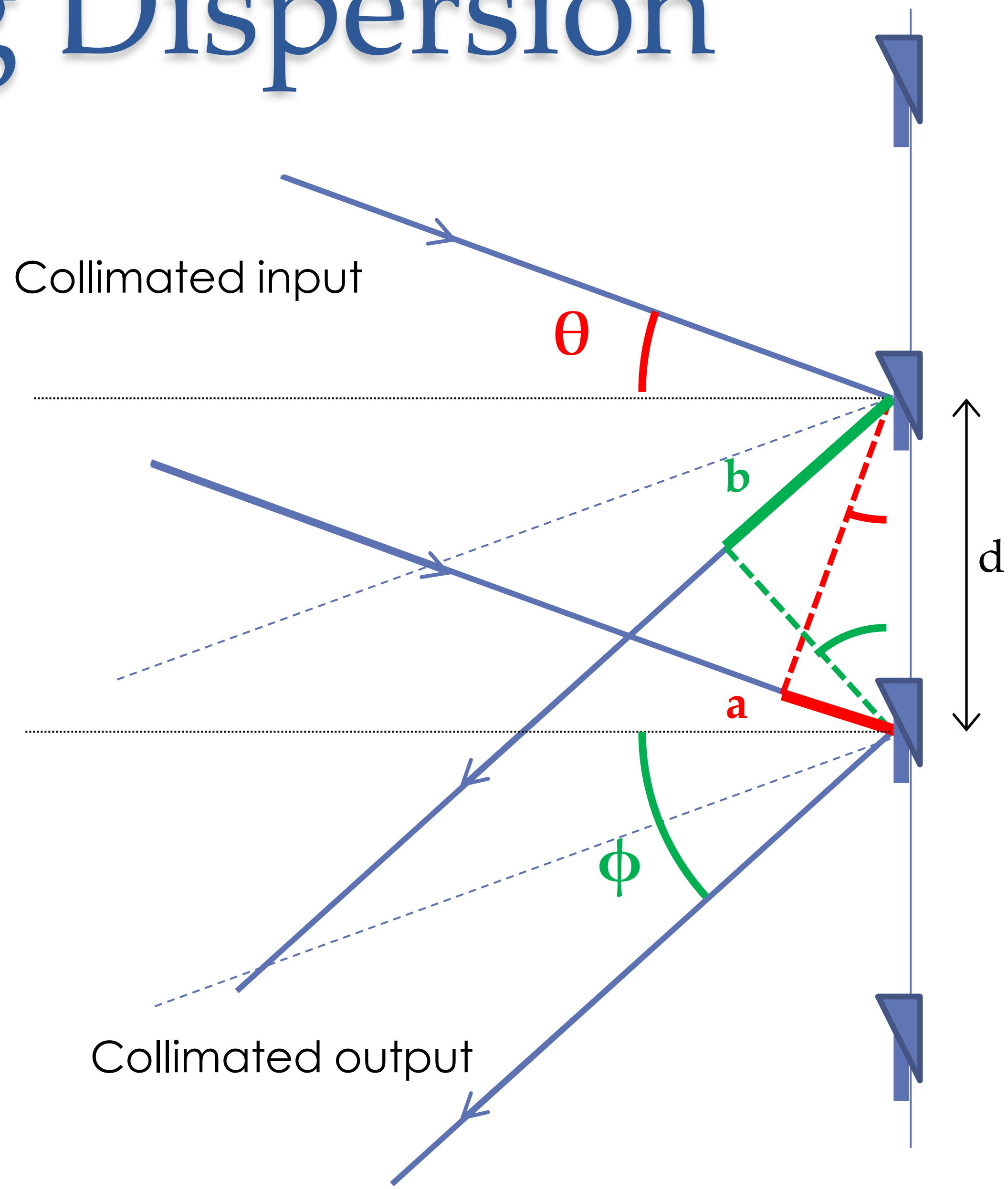
Note- angles are taken as positive if clockwise from normal.

Differentiating this gives us the "Angular Dispersion"

$$\frac{d\phi}{d\lambda} = \frac{m}{d\cos\phi}$$

This can be transformed into linear dispersion using a lens:

$$\frac{dx}{d\lambda} = \frac{m.f}{d\cos\phi}$$



Resolution - N-Slits

Phasor representation of interference

- Amplitude from each slit is represented by arrow length
- Phase is represented by angle to the horizontal“reference” phase

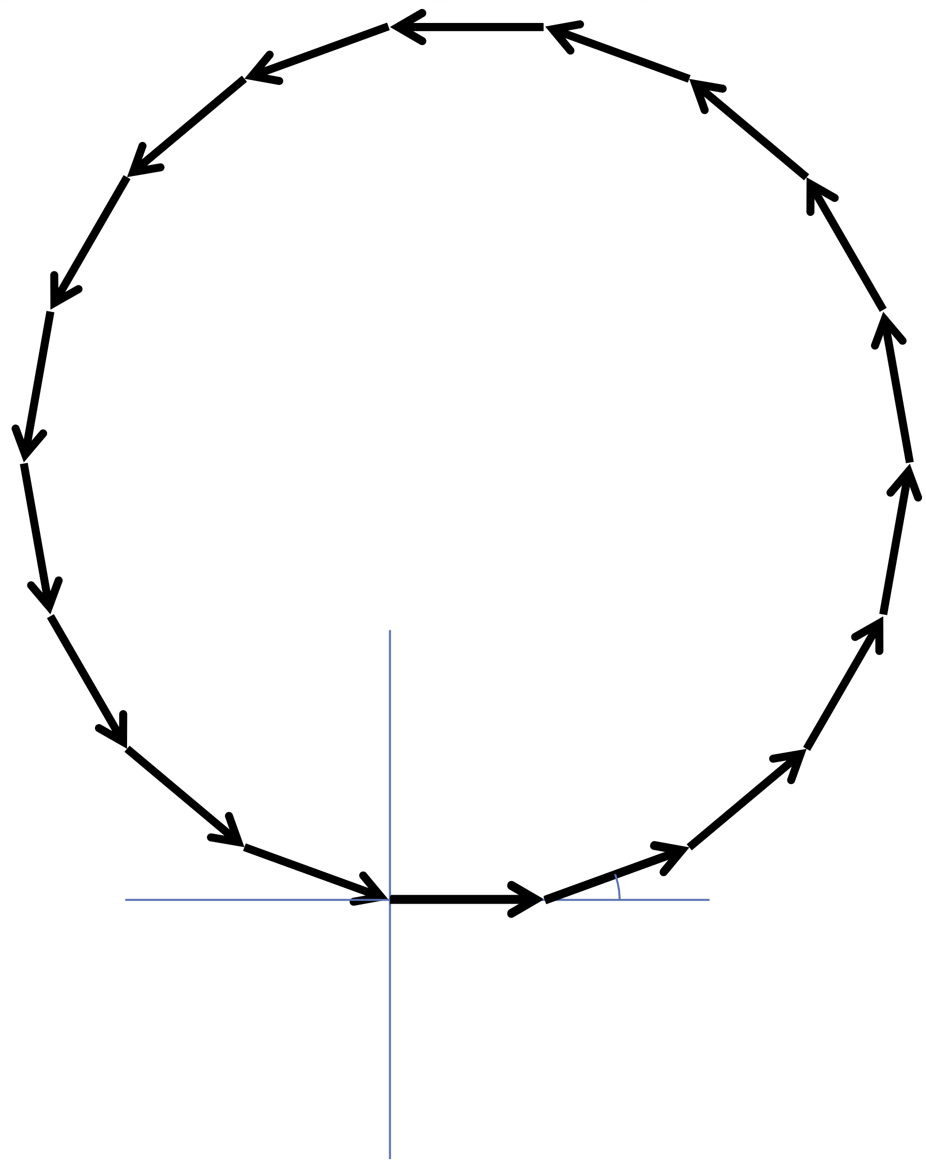
It is clear that more slits give a quicker angular extinction of a given wavelength

We can go further and say that resolution is proportional to number of slits illuminated

Resolvance, R

$$R = \frac{\lambda}{\Delta\lambda} = mN$$

Illuminate as much of the grating as possilble!

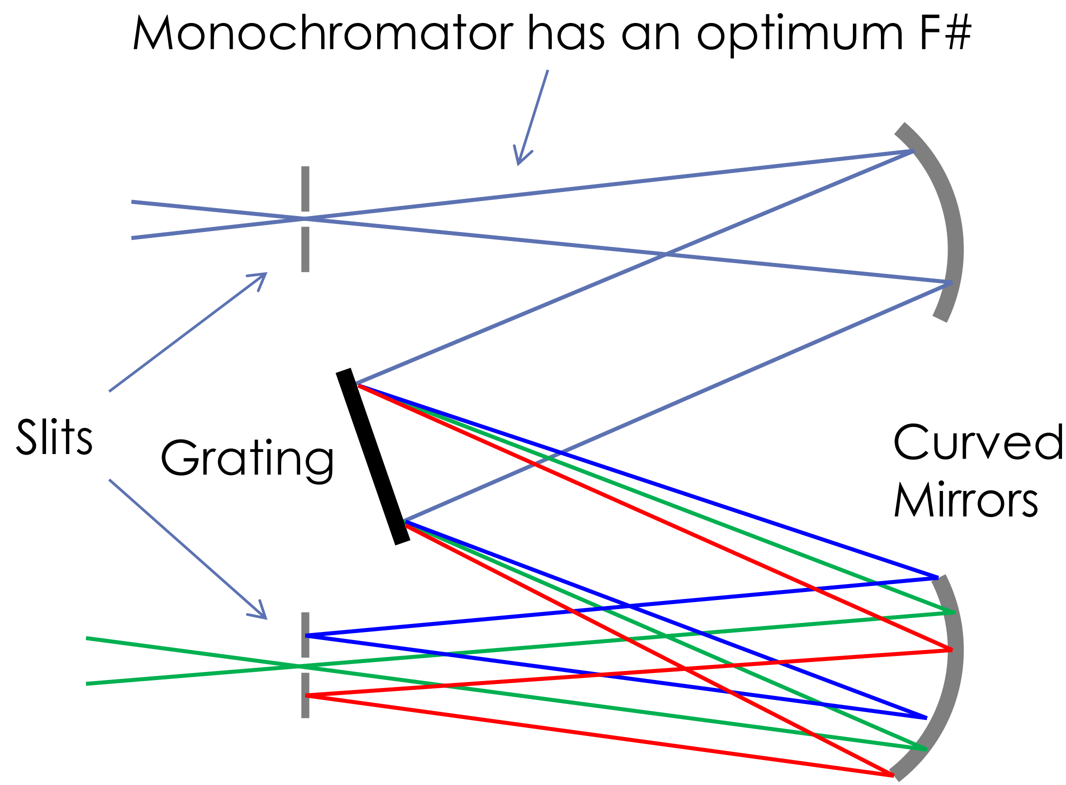


Monochromators

- A monochromator consists of
  - An entrance slit
  - Collimation optics
  - Dispersive element
  - Focussing optics
  - Exit slit

Resolution is dependent on slit widths

- To obtain a spectrum the wavelength must be tuned
  - Motorised grating angle
  - Replace slits with an array of sensors



Czerny-Turner design

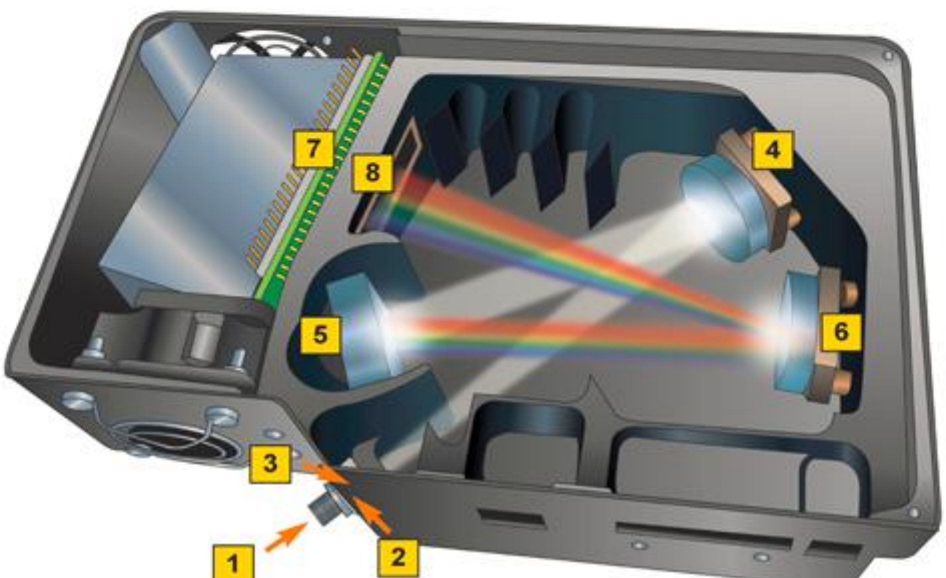
Examples

Ocean Optics CCD array design

- Resolution limited by pixel size
- Small and robust

Anritsu Optical Spectrum Analyser

- Rotating grating arrangement
- Large and precise



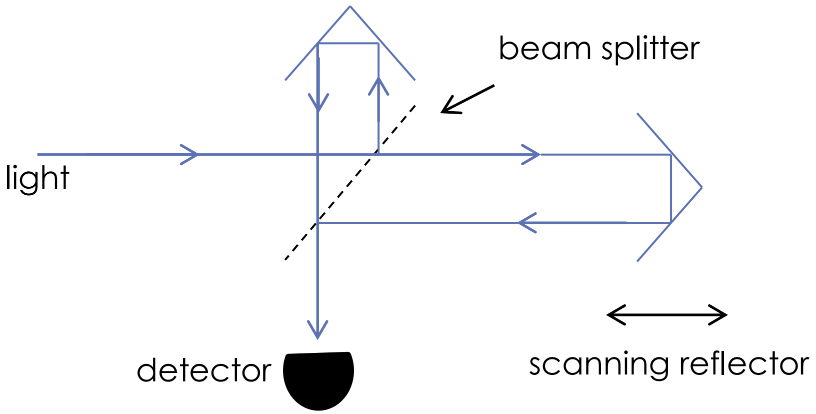
Interferometers

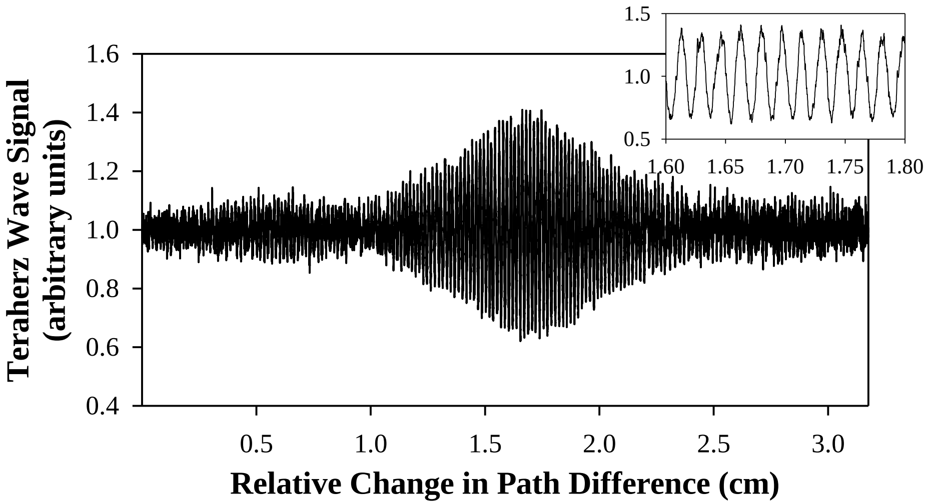
- 2-beam interferometers
  - Fourier transform spectroscopy

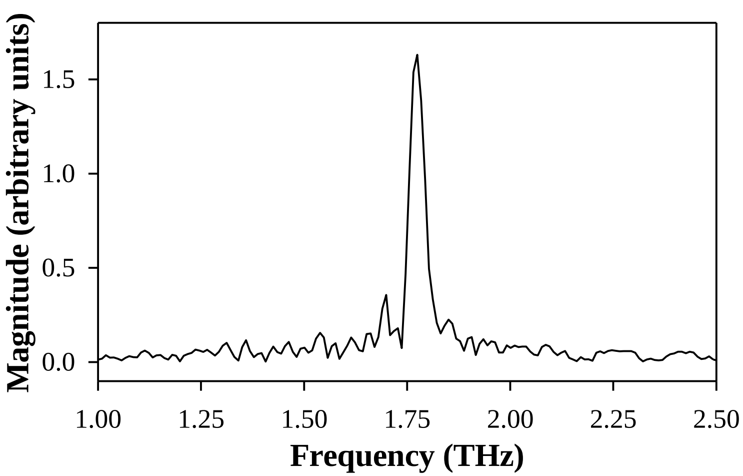
    broadband
  - Wavemeters – fringe counting

    Narrowband

    Can resolve modes of a laser







Interferometers

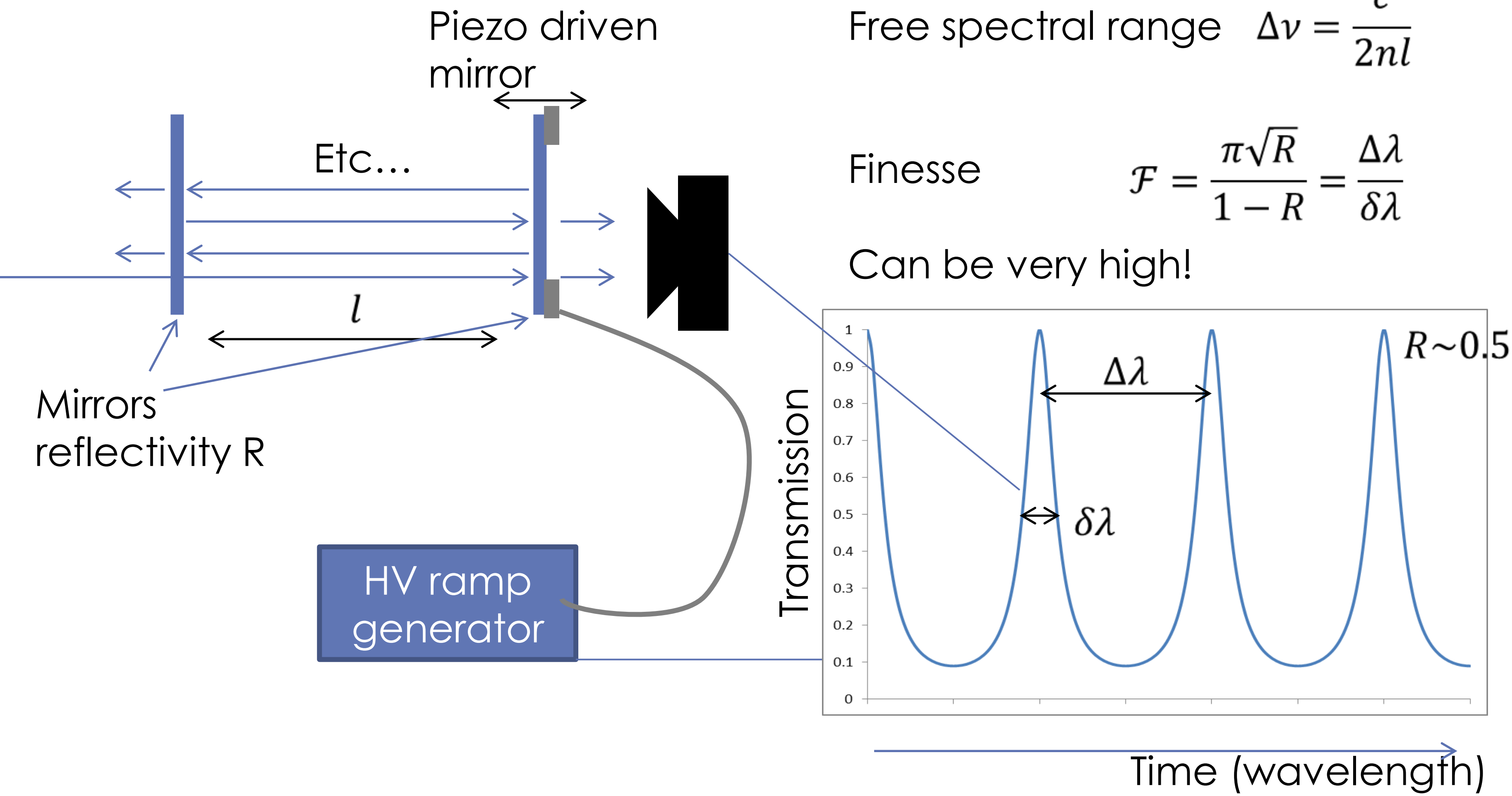
Multiple beam interference, the Fabry-Perot

Can only measure frequency differences – if difference < $\Delta\nu$

Free spectral range $\Delta\nu = \dfrac{c}{2nl}$

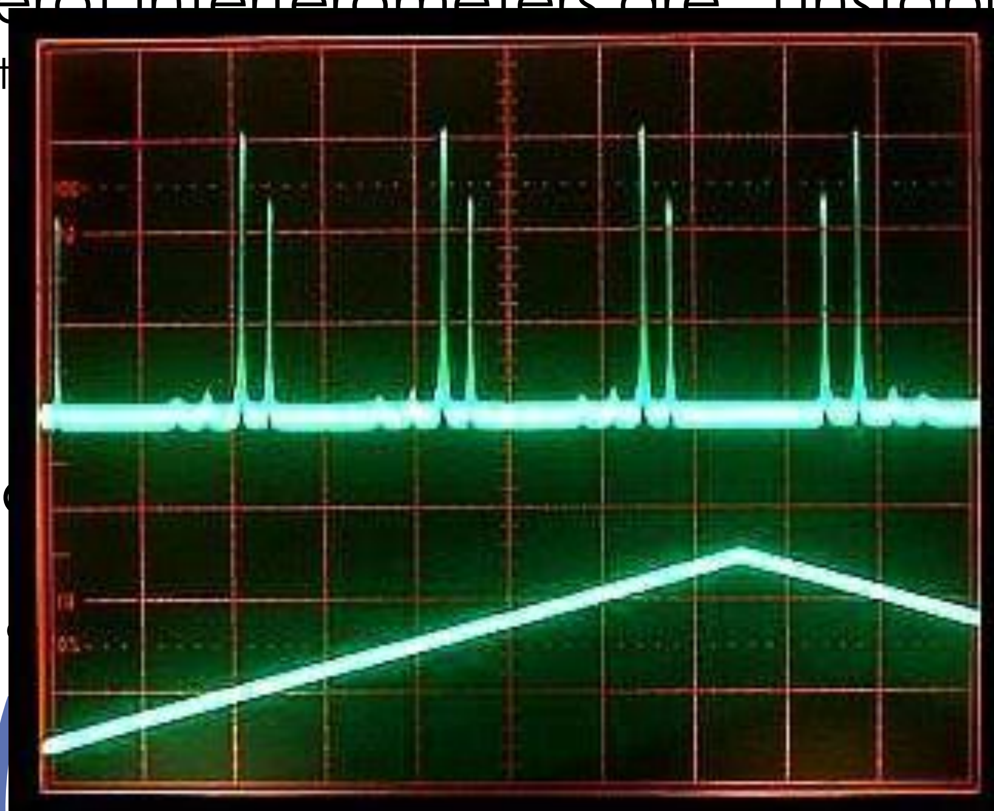
Finesse $\mathcal{F} = \dfrac{\pi\sqrt{R}}{1-R} = \dfrac{\Delta\lambda}{\delta\lambda}$

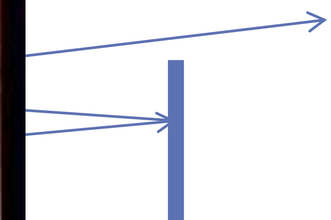
Can be very high!



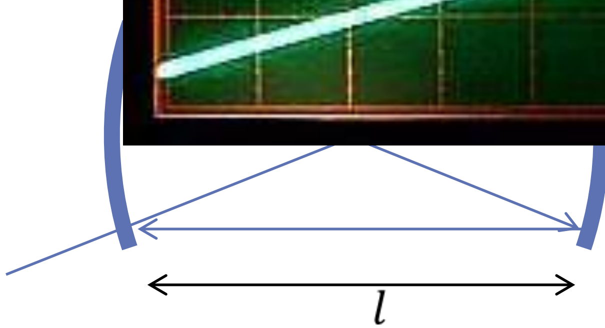
Confocal Interferometer

- Fabry Perot interferometers are "unstable"
  - Impract
  - diffraction
  - nment





- Confoc
  - On axis
  - Easy to



Off axis free spectral range

$$\Delta\nu = \frac{c}{4nl}$$

Temporal characteristics

- Pulse length
  - What is the peak power
- Power stability
  - On short timescales – noise
  - Day to day basis – is the system working properly
- Frequency and stablity
  - Important for synchronising your laser

"Nanosecond" Pulses

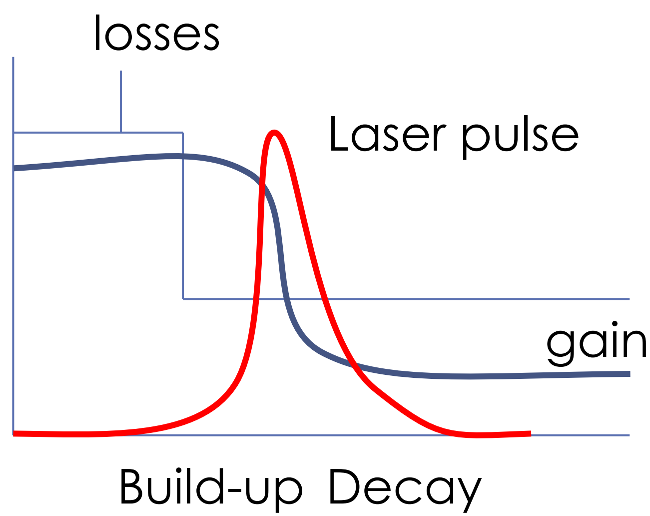
- Generated by Q-Switched lasers
- The Q-Switching process
    1. A laser is pumped with the resonant cavity spoiled (low-Q)
    2. The cavity is opened up (high-Q)
    3. The laser pulse then builds up (from noise photons)
    4. When the gain = loss the pulse stops building up
    5. Pulse decays through cavity losses

- Pulse length ~few ns
- Pulse timing jitter can be < 1ns

- If the laser has only a few cavity modes then mode beating can be a problem

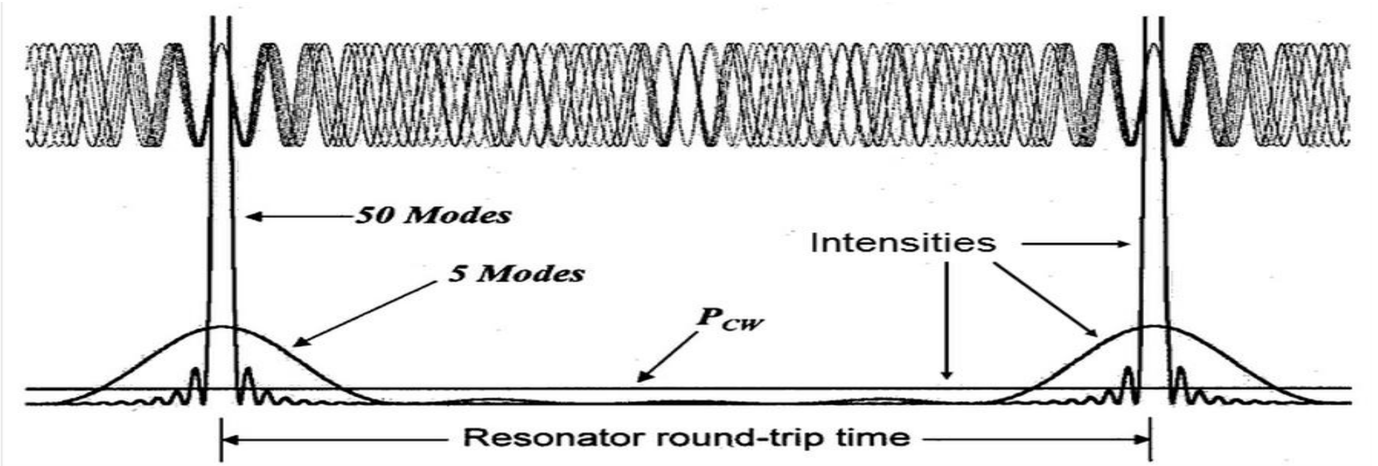
- Can also detect Q-Switching instabilities of modelocked lasers

This is all observable with off the shelf fast photodiodes and an oscilloscope



Modelocked Lasers

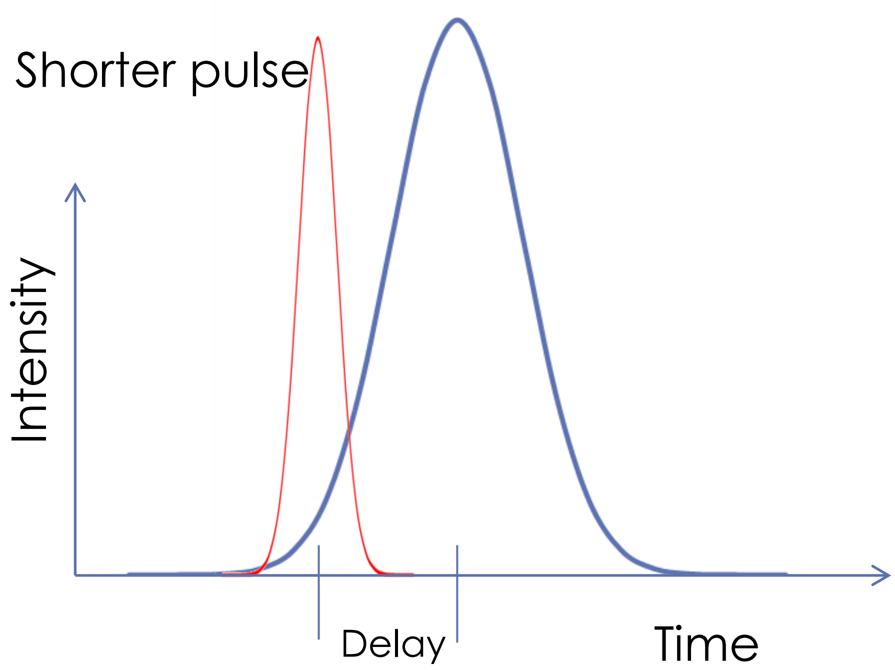
- By locking longitudinal modes in phase such they will only interfere constructively over a short time period, an ultra short pulse that propagates inside the laser cavity is formed

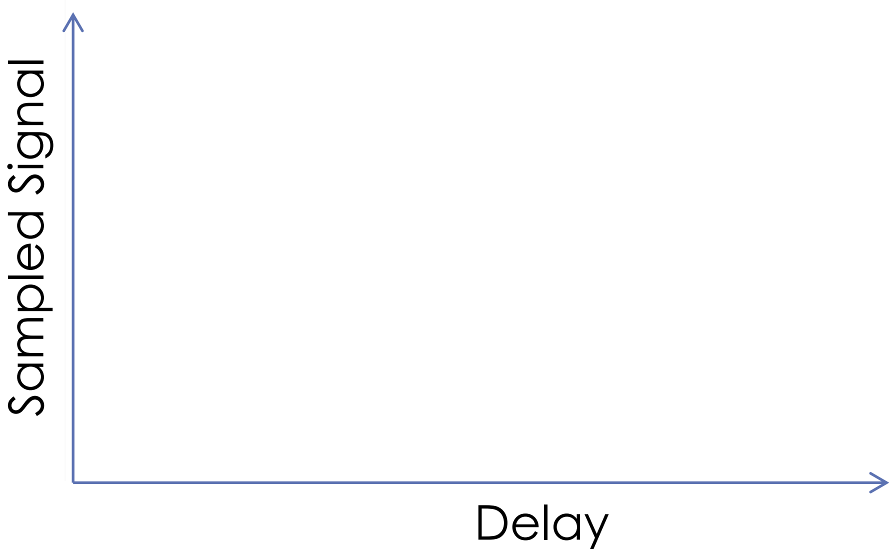


- Pulse width is related to the bandwidth through the Fourier Transform
- Pulses are typically in the range of 10s fs to several ps long!
  - Much too short to measure with a photodiode and scope!

The Problem

- How do we measure the temporal profile?
  - There are no detectors fast enough!
- If we had an even shorter pulse, could we use it to "sample" the pulse somehow

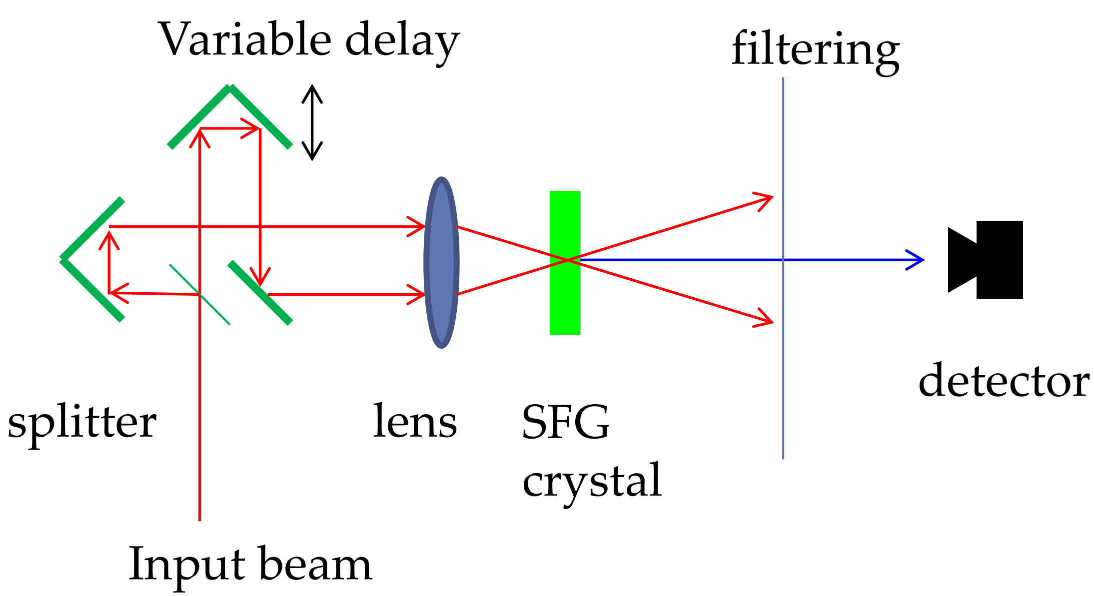




Intensity Autocorrelation

- We can use nonlinear optics as our gating method
  - Sum frequency generation
  - 2-photon absorption
- Generally you don't have a shorter pulse

  - use the pulse itself!



$$I_{ac}(\tau) = \int I(t)I(t-\tau)dt$$

Time bandwidth product

What does this tell us about the pulse?

- We can compare I_{ac} with the calculated autocorrelation of a guess at the temporal profile e.g. Gaussian, $Sech^2$, Lorentzian
- If we also measure the spectrum we can calculate the "time-bandwidth product" - TBP

What is it?

- If we take the Fourier transform of a given pulse shape we can find the minimum spectral bandwidth required to recreate the pulse

  (this assumes a constant spectral phase)
- The product of the temporal and spectral FWHM for a given pulse envelope is a constant (as the pulse lengthens, the required spectrum narrows)

So, by comparing the measured TBP with the theoretical value, we can check to see if we are at the "transform limit"

But what if we aren't?...

Pulse Profile	Transform Limited TBP
Gaussian	~0.44
$Sech^2$	~0.315

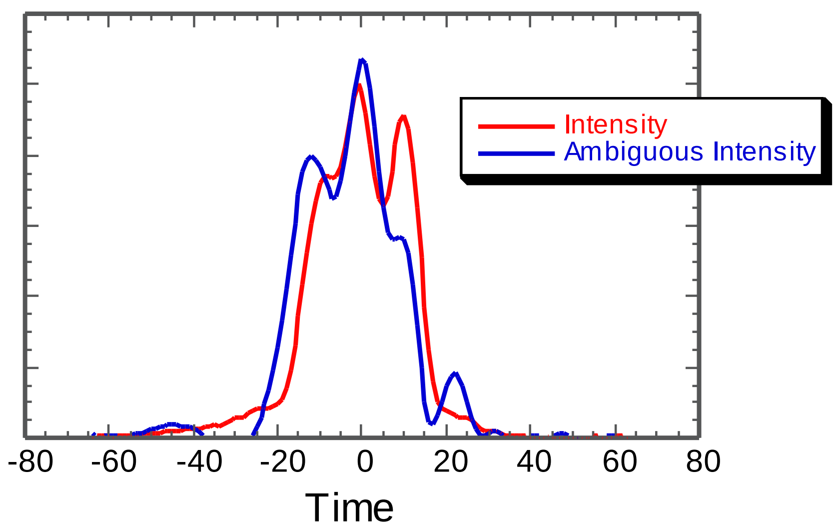
Issues with Autocorrelation

How do we get from the AC back to the real temporal profile? – We can't!

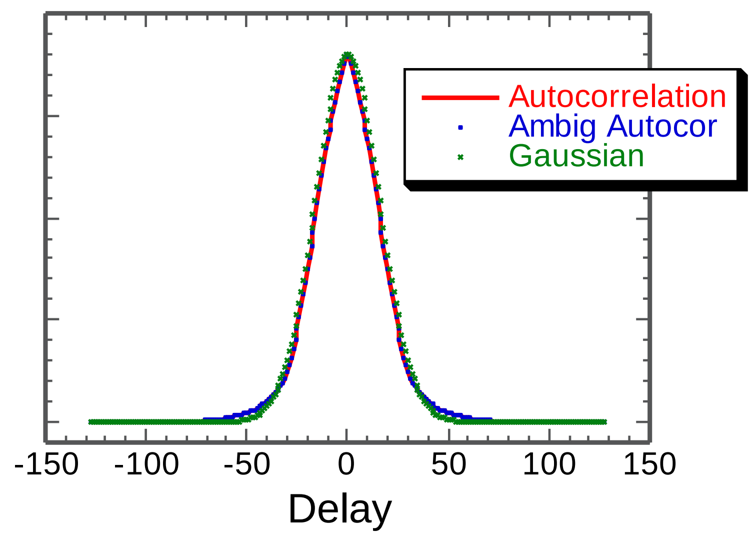
There are a number of problems with the AC:

- All ACs are symmetrical!
- The more complex the pulse, the more "Gaussian" the AC looks
- The AC is degenerate – multiple profiles give the same AC

Intensity



Autocorrelation



What do we need to know?

- To get a full picture of the pulse we need to know the **intensity <u>and</u> phase vs. time or frequency**

In the time domain: $E(t) = Re\left(\sqrt{I(t)}e^{i(\omega_o t-\phi(t))}\right)$

"Carrier" frequency

Can't measure

In the frequency domain: $\tilde{E}(\omega)=\sqrt{S(\omega)}e^{-i\varphi(\omega)}$

Spectrum

Spectral Phase

The Spectrogram

- The "spectrogram" is the collected spectra of the pulse when sampled with a gate function at various time delays

$$I(\omega, t) \propto \left| \int E(t)\, g(t-\tau) e^{-i\omega t} dt \right|^2$$

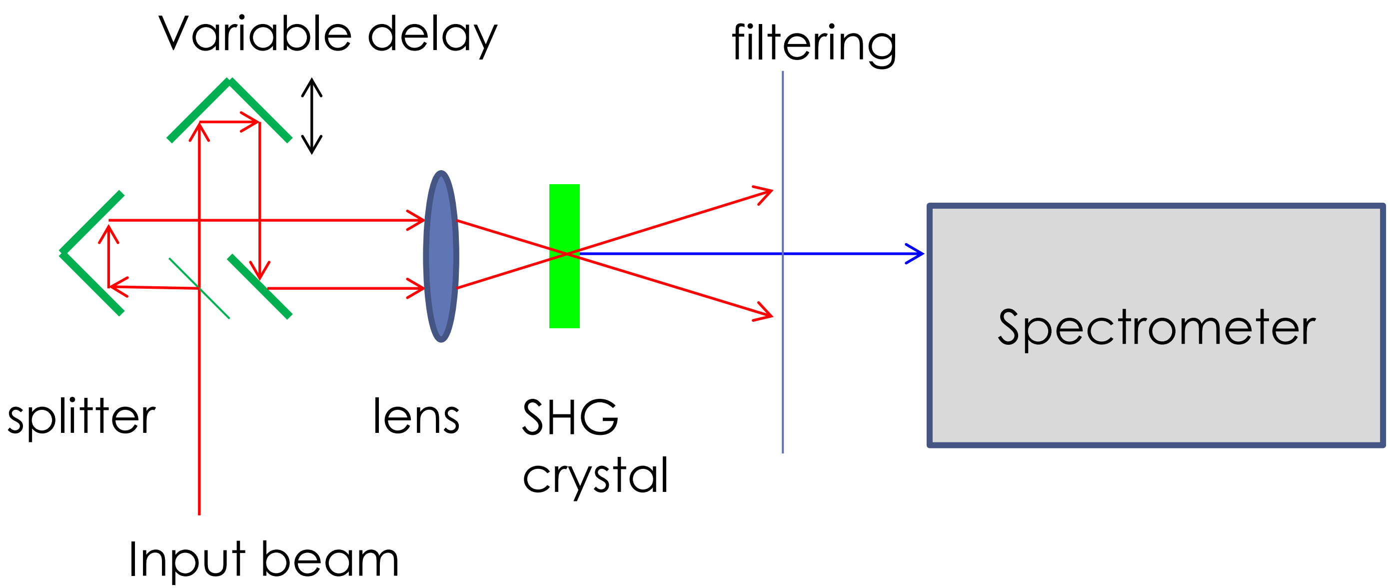
If $g(t-\tau)$ and $I(\omega, t)$ are known, $E(t)$ can be retrieved!
(i.e. there are unique solutions for this problem, unlike the AC)

If we don't know $g(t-\tau)$, (i.e. if it were $E(t-\tau)$), there are still robust algorithms for finding $E(t)$!

So how do we measure the spectrogram?

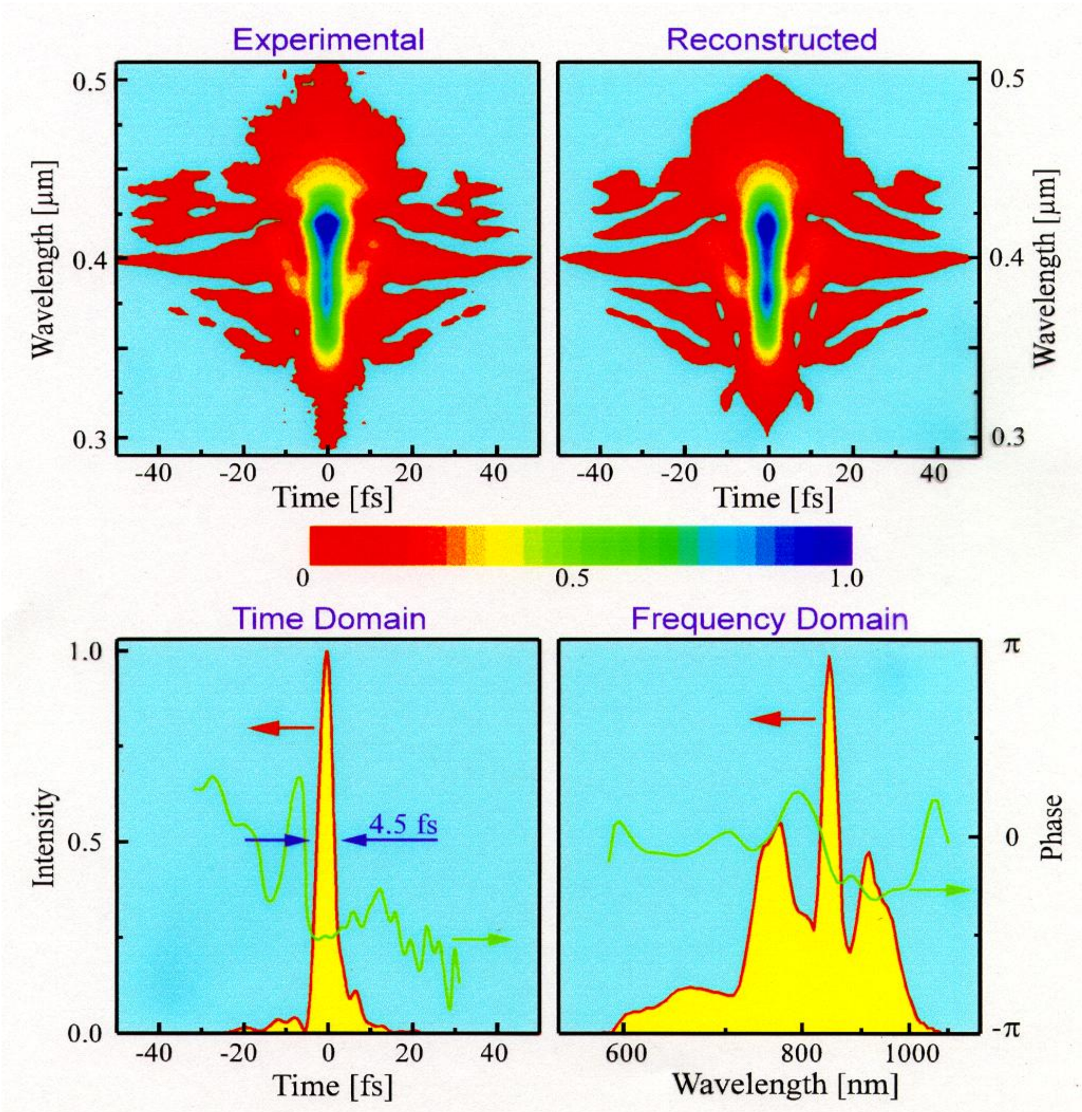
Measure the Spectrogram

- By placing a spectrometer after the autocorrelator, instead of an intensity detector



- This technique is known as Frequency Resolved Optical Gating, or simply "FROG"

FROG Example

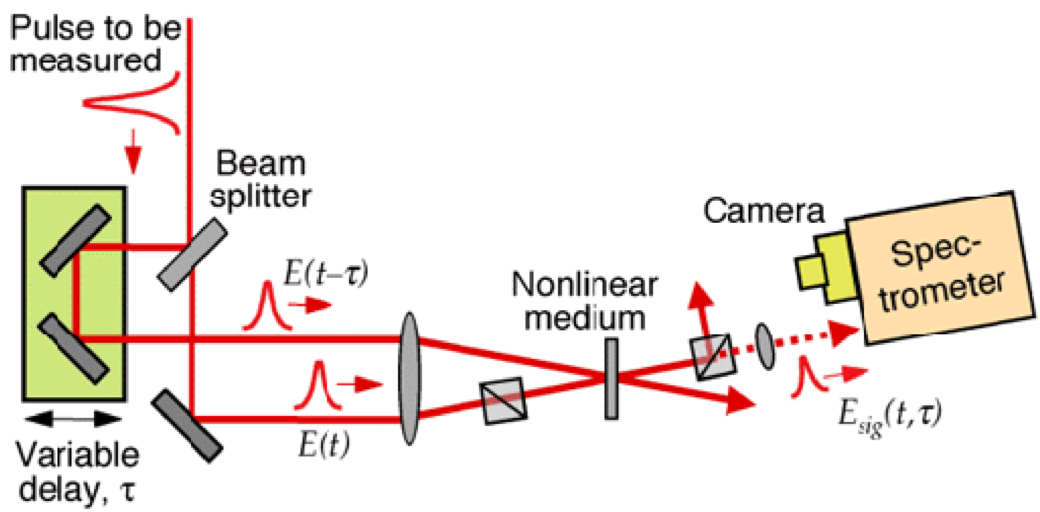


4.5 fs pulse!

Baltuska, Pshenichnikov, and Weirsma, J. Quant. Electron., 35, 459 (1999).

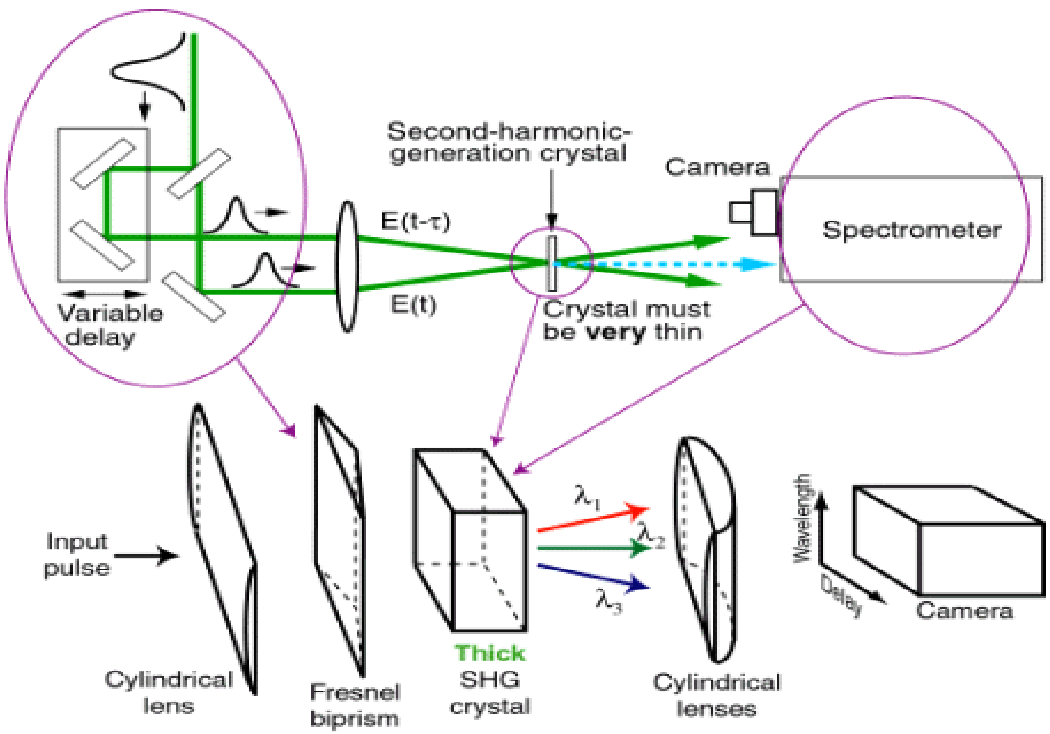
More FROGs

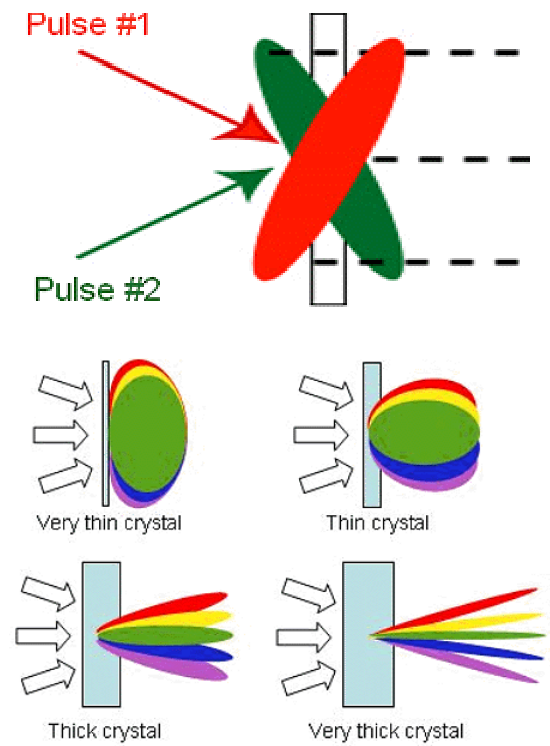
- SHG is not the only exploitable nonlinear effect e.g.
  - Polarisation Gating
  - Optical Parametric Amplification (attojoule pulses measured)
  - Difference Frequency Generation (extends frequency range)



- There is also a very simple version - GRENOUILLE

GRENOUILLE

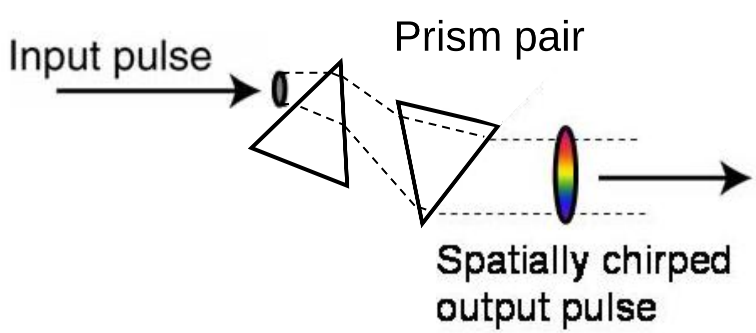


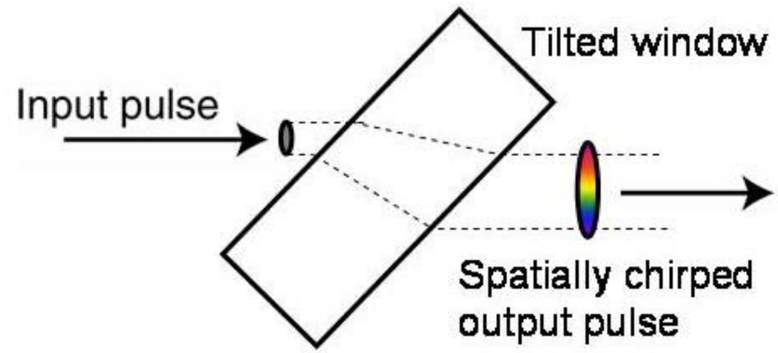


- Grating Eliminated No-nonsense Observation of Ultrafast Laser Light E-fields…
- Spectrometer is replaced by a thick nonlinear crystal and a CCD – the phasematching condition now determines the angular spread (will discuss phasematching this afternoon!)
- Delay stage has been replaced by a Fresnel Biprism, thereby mapping the delay across the CCD

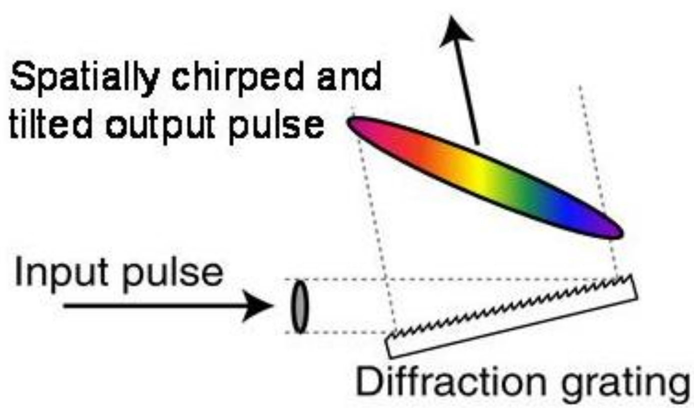
Spatio-Temporal Distortions

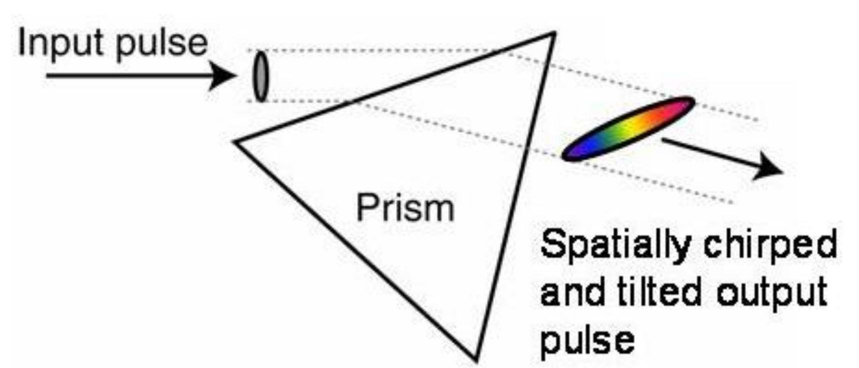
Prism pairs and simple tilted windows cause “spatial chirp.”



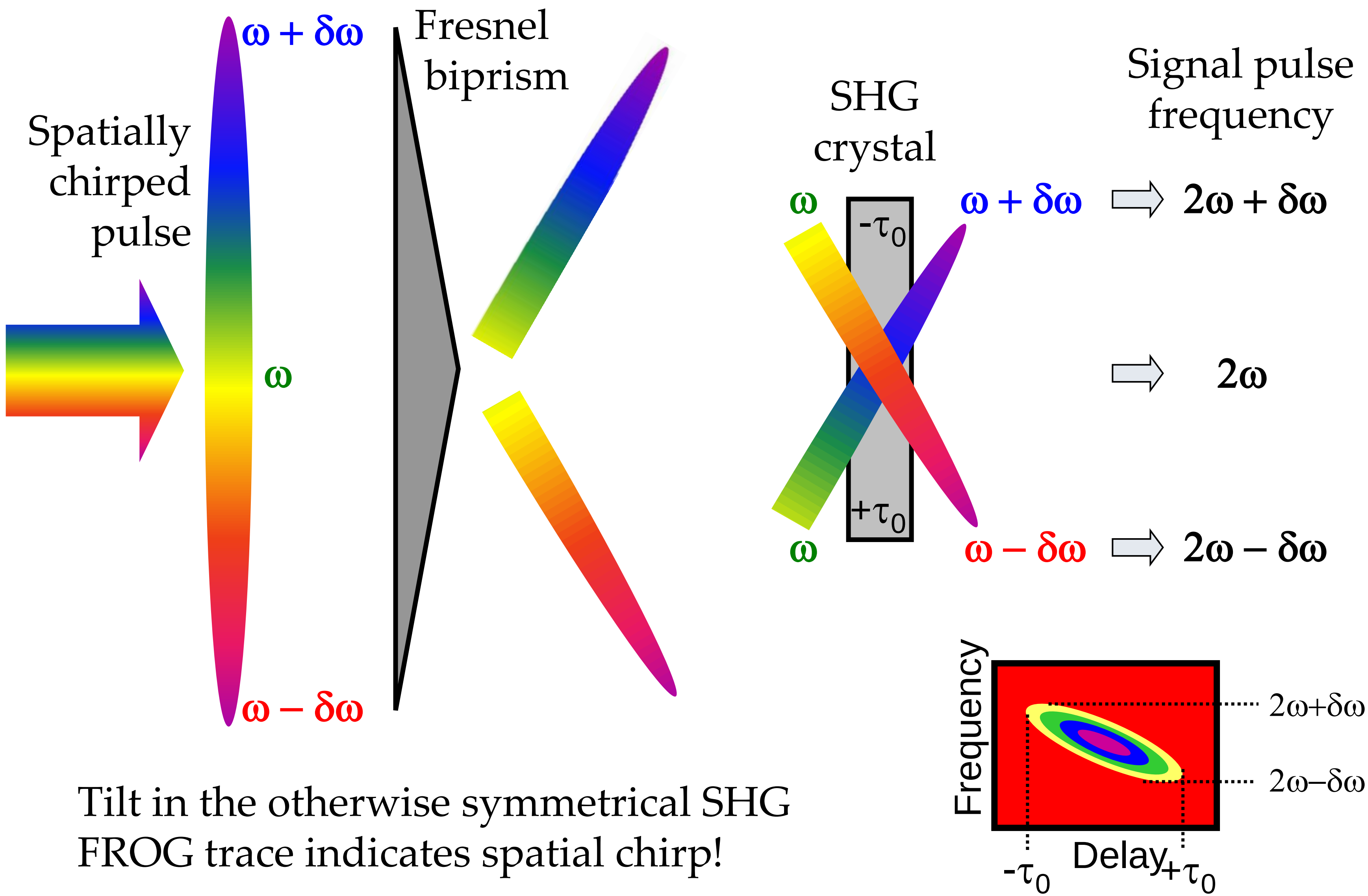


Gratings and prisms cause both spatial chirp and “pulse-front tilt.”



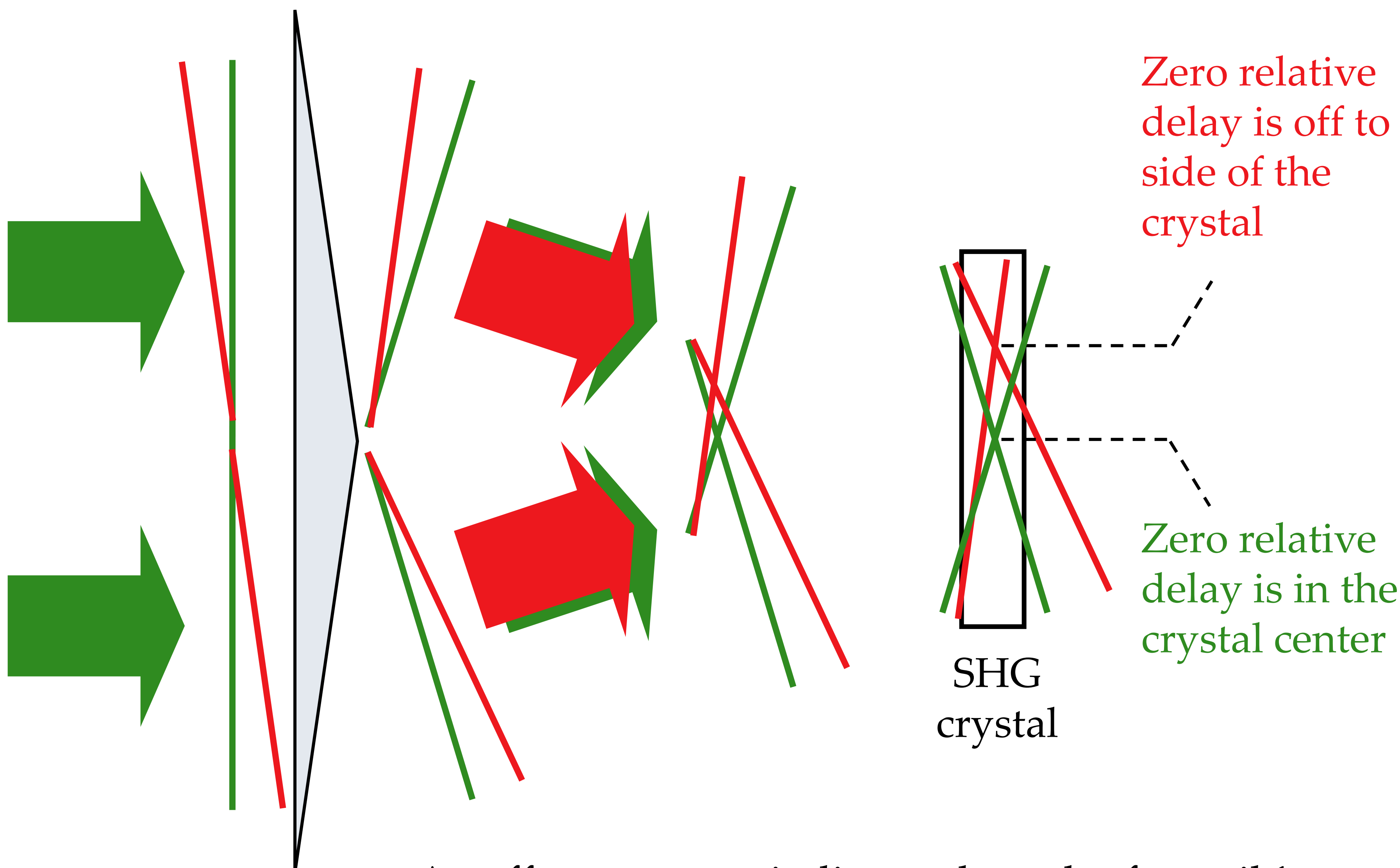


Spatial Chirp



Tilt in the otherwise symmetrical SHG FROG trace indicates spatial chirp!

Pulse-front Tilt



An off-center trace indicates the pulse front tilt!

*Disclaimer: Other Techniques Are Available!

- Detectors
  - Bolometers
  - Golay cells
  - Schottcky diodes
- Pulse characterisation techniques
  - Interferometric Autocorrelation
  - Even more varieties of FROG!
  - SPIDER - Spectral phase interferometry for direct electric-field reconstruction
    requires constant phase so not suitable for some applications
    e.g. fluorescence spectroscopy
  - MIIPS - Multiphoton intrapulse interference phase scan
- And More!

The End

• • •

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