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Fast Diagnostics Optical and X-ray

Tony Dymoke-Bradshaw
Kentech Instruments Ltd., Unit 9, Hall Farm Workshops,
South Moreton, Didcot, Oxon, OX11 9AG, U.K.
Contact: tony@kentech.co.uk   Web: www.kentech.co.uk

these notes will be posted at
http://www.kentech.co.uk/Tutorials.html

Formerly with Plasma Physics Group at Imperial College
Experience of streak cameras, fast gated cameras, fast high voltage pulsers, etc.
Many such cameras are used at laser labs around the world.
Increasingly these camera systems are being used outside this area by chemists and biochemists.

Scope of this talk

- Streak Cameras, Framing cameras (Gated cameras), both x-ray and visible.
- General principles.
- Typical limiting parameters.
- Restrictions on use, radiation, light levels.
- High rate Imagers and Applications
- Pulse sources for these types of diagnostics.
- Application of these pulse sources to driving Pockels cells.

General Principles of Fast Diagnostics

- Reduce data acquisition speed, intermediate data storage
- Use non linearity to increase bandwidth.

- Convert time into space. e.g. streak cameras, auto/cross correlators, oscilloscopes, time → spectrum → space.
- Time dilation e.g. for neutron , time of flight.

- Typical bandwidth of electronics, few GHz; multichannel systems are expensive. Many GHz systems are very expensive, hence alternative technologies are used.
- Time scale for experiments, tens of ns down to 0.1ps. Latest streak cameras can achieve ~0.1ps.

- Single shot recording v. repetitive mode, multishot sampling, averaging, sysnchroscan

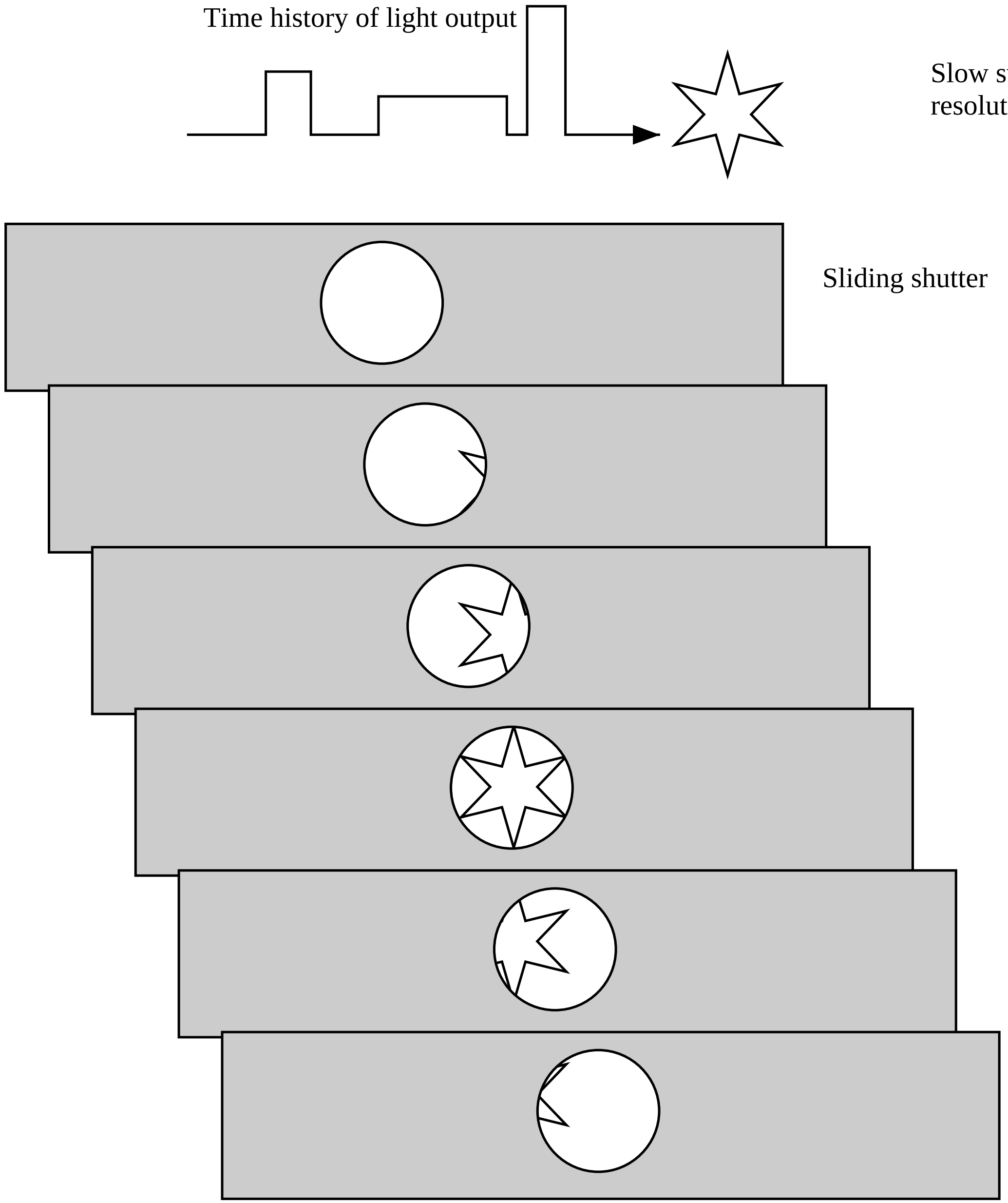
Nonlinear Techniques

- Note $\sin^2(\omega t) \rightarrow$ terms with $\sin(2\omega t)$; higher powers
- Non-linearity can give a higher bandwidth.

Examples

- Streak cameras linear ramp, linear sweep but electron beam is swept across a resolution element, very nonlinear, very high bandwidth.
- Cathode gating
- MCP gating
- Pockels cells

Nonlinear Effects 1

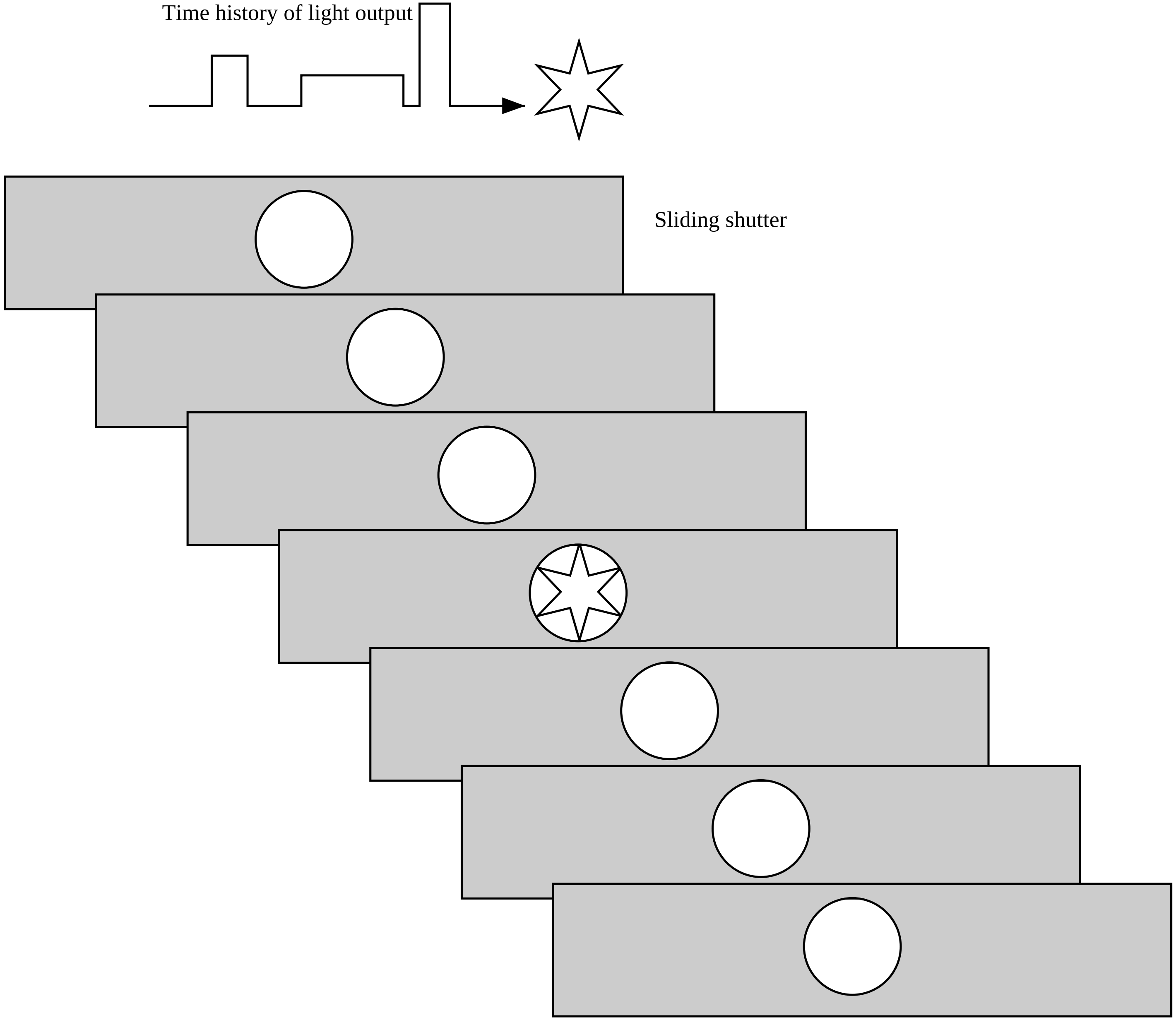


Time history of light output

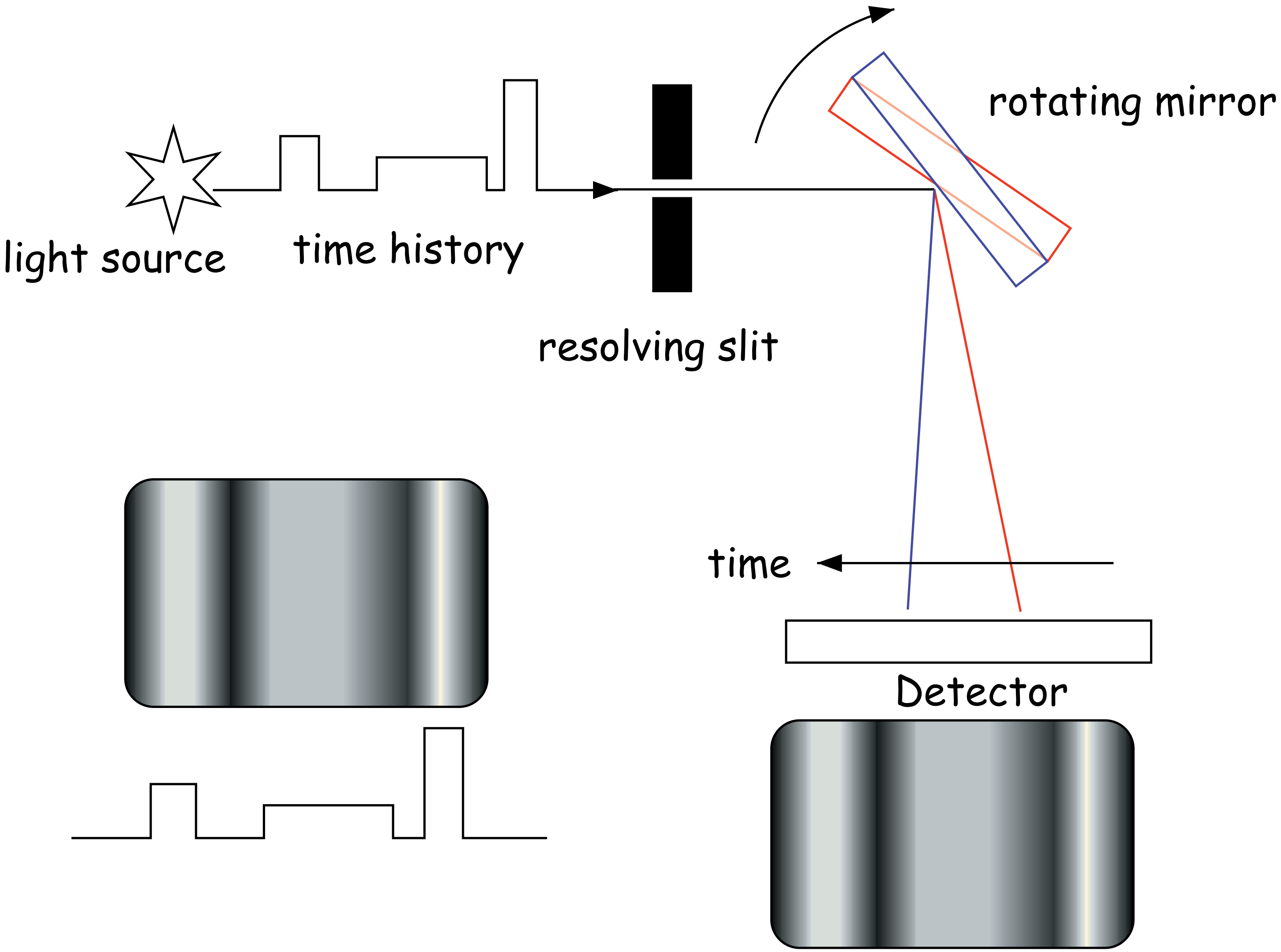
Slow sweep gives poorer time resolution.

Sliding shutter

Nonlinear Effects 2



The Simplest Streak Camera



rotating mirror

light source

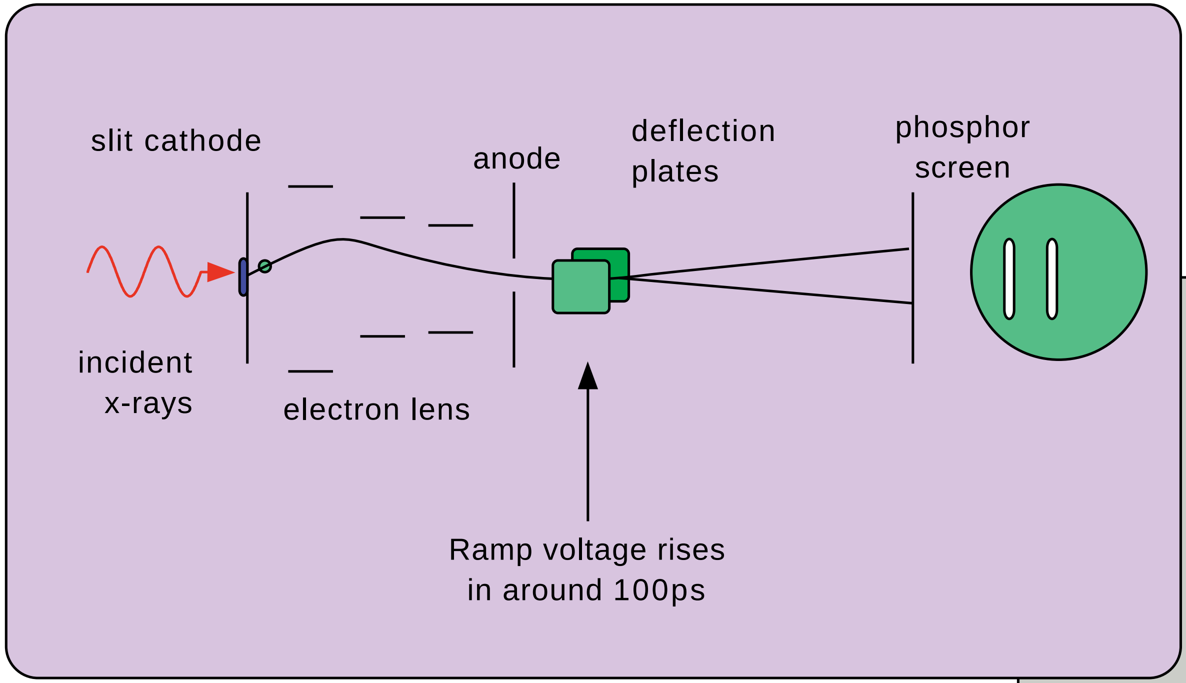
time history

resolving slit

time

Detector

Streak Camera



slit cathode

anode

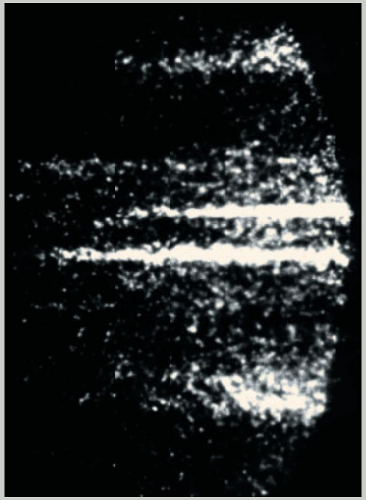
deflection plates

phosphor screen

incident x-rays

electron lens

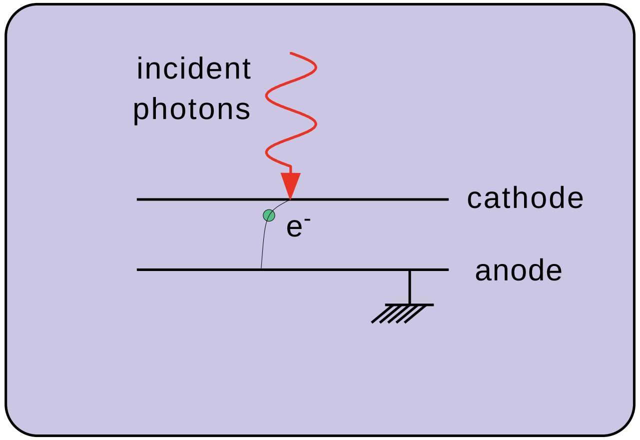
Ramp voltage rises in around 100ps

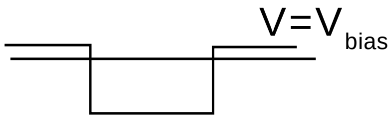


Sweeps of x-ray spectral lines Al Heγ (6.31Å) and Si Lyman α (6.17Å) from a layered target. The sweep calibration gives 3.3ps mm^{-1} at the camera output and a 7ps delay in the onset of Si emission

Nonlinear Effects 3

Cathode Gating

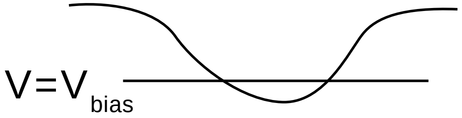




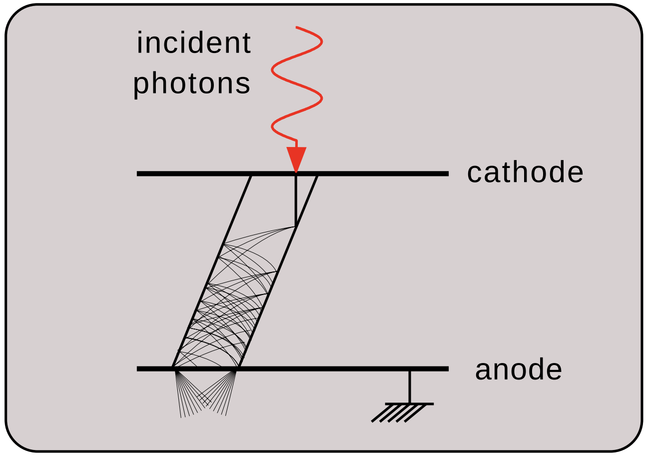
I=0 for V>0

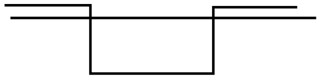
I= I_{pc} for V<0

Even slow pulses can give high bandwidth information.



Microchannel Plate Gating





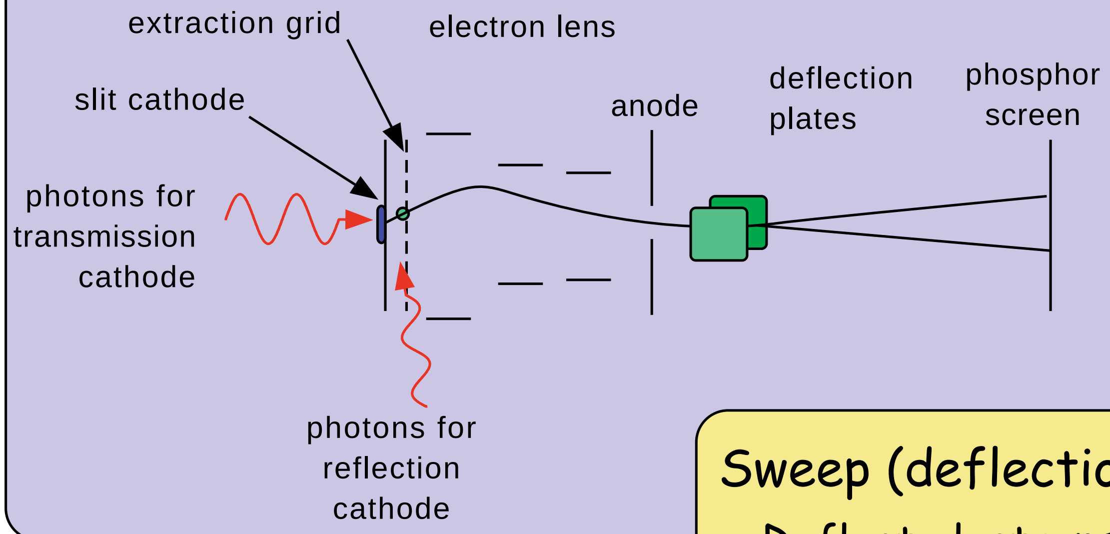
gain α V^n

n > 1

Even slow pulses can give high bandwidth information.

Streak Cameras: An introduction

A typical streak tube



Electron Current Density

Space charge at the cathode and anode can defocus the beam and limit spatial resolution.

Extraction grid

Accelerates electrons in a high field region to reduce the transit time variations through the tube

Sweep (deflection) plates

Deflect electrons across output detector, time → space.

Length and separation of sweep plates determine deflection sensitivity.

Electrons should not pass too close to the plate.

The electrons should spend less time in the deflection region than the rise time of the ramp drive otherwise the ramp effect will not be linear.

Streak Cameras: Continued (2)

Cathodes

X-ray	Au, CsI, KI, KBr, CuI
Optical	S1, S25, S20 etc

Substrates

X-ray	None, Sapphire, Quartz, C, Formvar, Mylar
Optical	Sapphire, Quartz, Glass, fibre optic

Notes

Gold is very hardy but has a 3ps response and a lower QE than the others for x-rays. Good for VUV.

CsI has very high QE especially for low density CsI (foam). Foam cathodes are more resistant to atmospheric conditions.

KI has the best temporal response but a lower QE for x-rays than KBr which is slightly slower. KI energy spread ~1.1eV

Notes

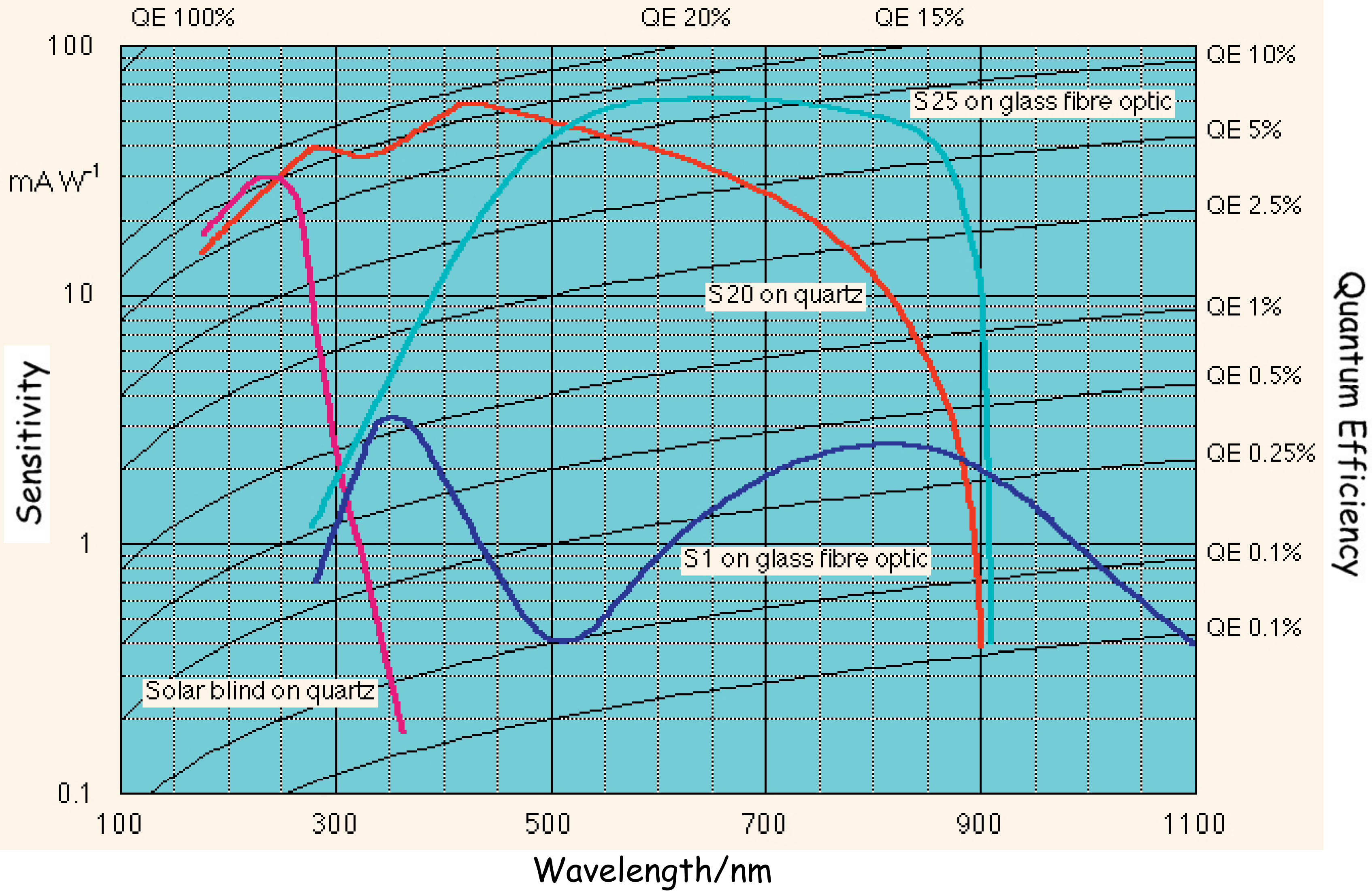
Sapphire and Quartz are good in the UV or to support reflection cathodes.

Mylar is good above a few keV.

Formvar and Carbon (hard to make) are good for soft x-rays.

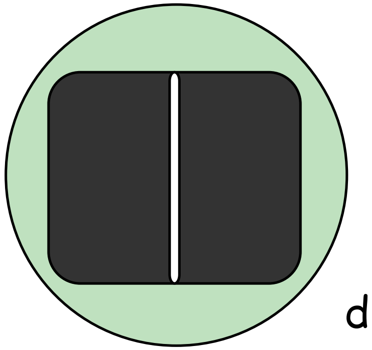
Fibre Optic is poor for blue light and also watch out for core size at longer wavelengths.

Typical Photocathode Responses



How to Time a Streak camera

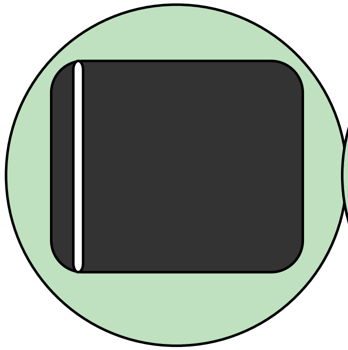
Focus camera



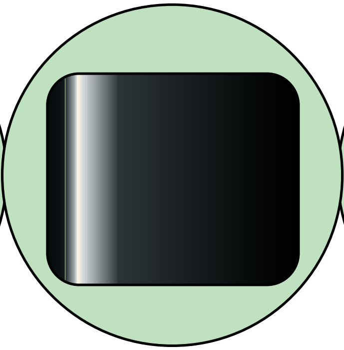
Focus, Synch. and Operate modes.

Focus	No sweeping. Image in centre.
Synch.	Image starts at screen centre or on one side, but on screen. Sweep occurs on trigger.
Operate	Image starts off screen. Sweep occurs on trigger.

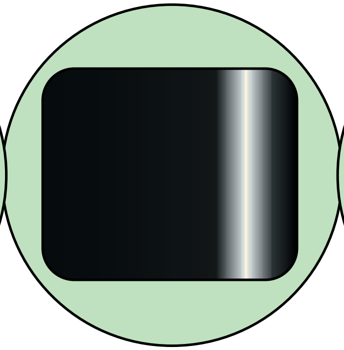
direction of sweep



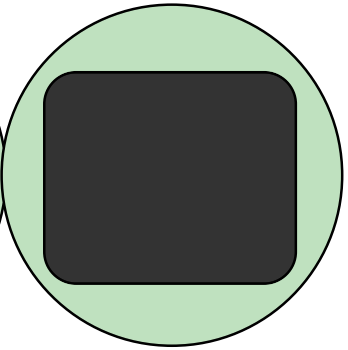
Synch.
trigger much too late



Synch.
trigger slightly late

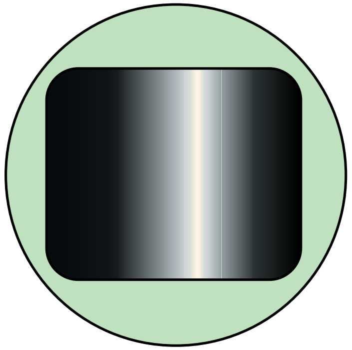


Synch.
trigger timing OK



Synch.
trigger too early

Operate



How to calibrate the time base of a Streak camera

Method 1 (preferred)

Illuminate the cathode with two or more pulses separated by a moderate fraction of the estimated temporal window of the camera. For optical systems an etalon can provide absolute measurement.

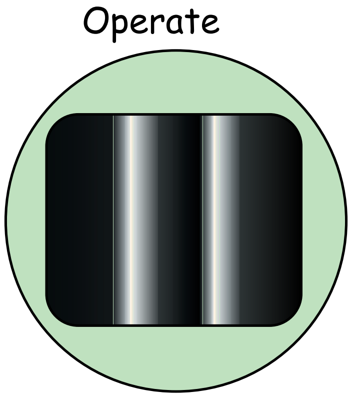
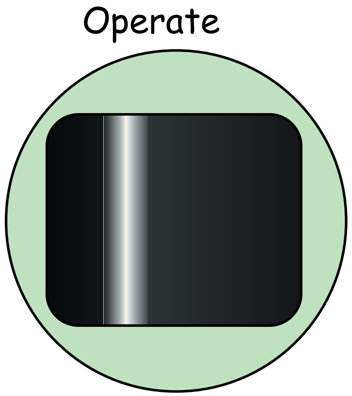


Image separation gives sweep speed.

Method 2 (needs low trigger jitter)

Illuminate the cathode with one pulse. Record image and repeat with known trigger delay change. This is no good at high sweep speeds as the jitter is far too high.



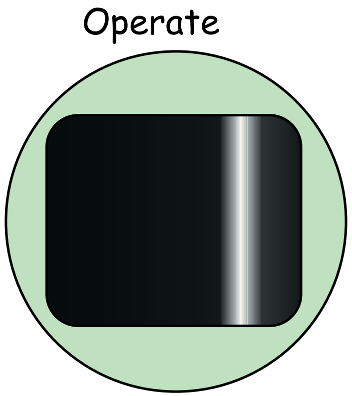


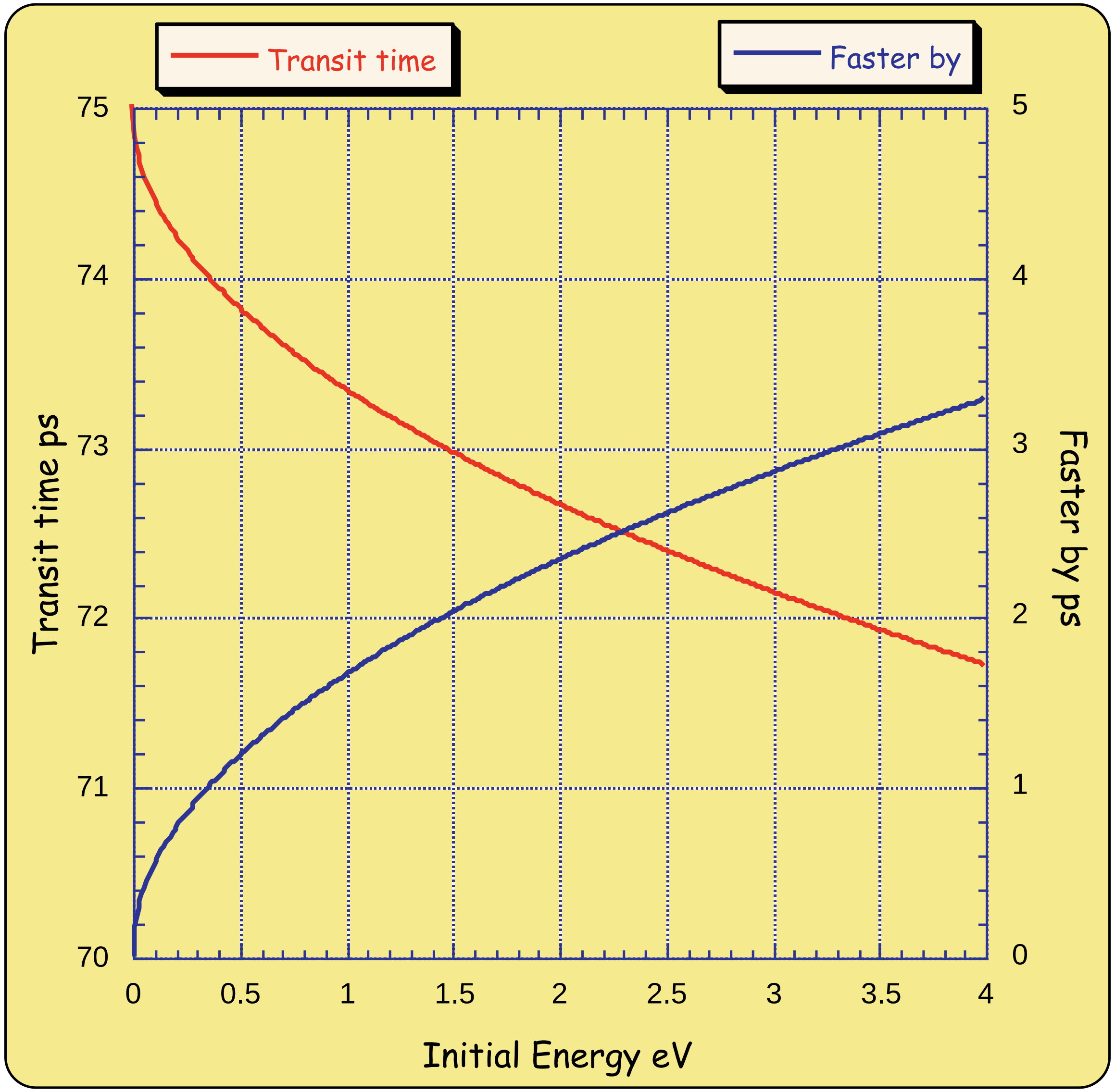
Image movement gives sweep speed.

Factors Contributing to the Time Resolution of a Streak Tube

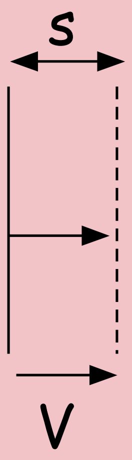
Spread in the arrival time and position of electrons produced by a single event at the cathode.

The width of the image of the slit in the detector, combined with the sweep speed also contributes to the time resolution.

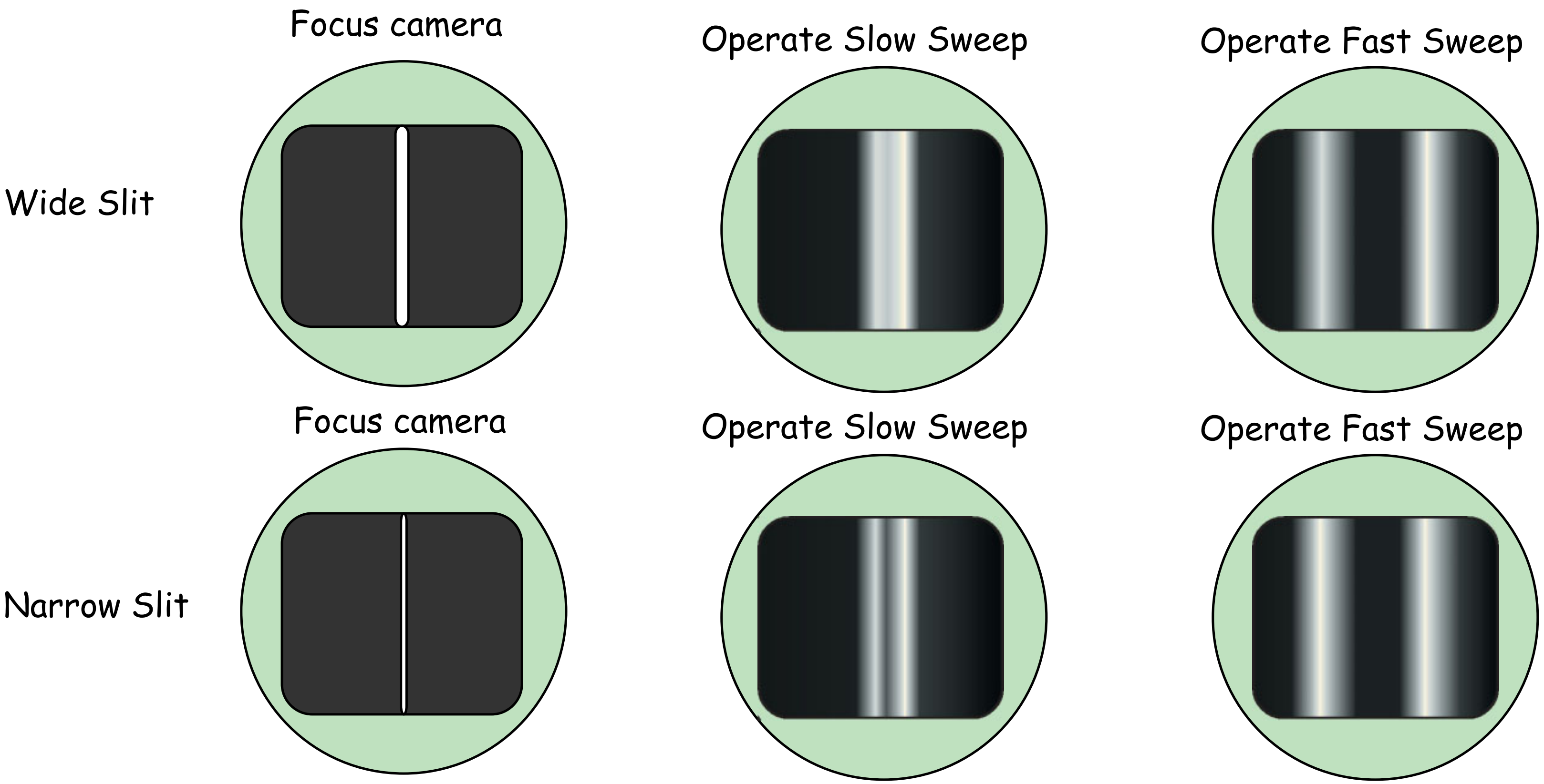
Variations in Transit Time (2)



Plot showing effect of initial energy on transit time spread for 2kV across a 1mm gap.



Effect of Finite Slit Width



The spatial resolution in the temporal direction contributes to the temporal resolution. In addition the input slit width determines the signal level. One has to find a compromise value for the input slit width that maintains a sufficient signal without reducing the temporal resolution below what is required. This effect can be mitigated by increasing the sweep speed but this reduces the temporal window. If the system jitter is not low, there is a useful limit on the sweep speeds. Windows in the 50ps regime are typically the lowest used regularly.

Image Detection and Recording

Topics	Film, Intensifiers, CCD, Directly excited back thinned CCD, resolution, sensitivity, space charge issues.
Film	High resolution, moderate sensitivity, non linear, reciprocity failure, pre and post fogging. Calibrated development. Slow turnaround.
CCD	Low to moderate resolution, high sensitivity, linear. Coupling issues. Capital cost

Image Detection and Recording, Intensifiers

Flat Field proximity focussed devices.

Gain of few 10^3 QE ~ 10% Low noise amplification

Expensive, requires vacuum transfer technology and in vacuuo welding.

Limiting Resolution typically 30 line pairs/mm.

Fibre Optic input and output.

Power supply must be carefully made. Sensitive to electrical abuse.

Indium seals very fragile do not solder leads back on, get them welded.

MCP channels saturate.

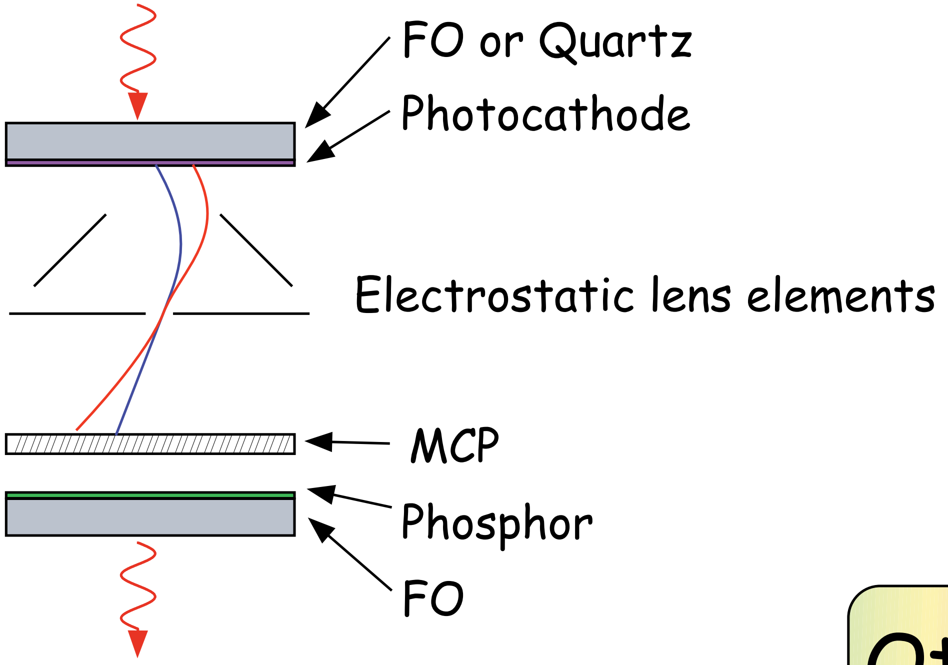
Cathode gating relatively easy but detector will still MCP dark current.

Electron Lens coupled devices.

Cheaper, distortion, no cathode gating possible, MCP gating possible.

Some are of glass construction, fragile.

First Generation Image intensifiers



Other Image intensifiers

1 Gen 1 with no MCP
2 Loop focussed devices
3 Diodes and diode stacks

Image Intensifiers GEN. 2, 3...

Cathodes S1, S20, S25, GEN3

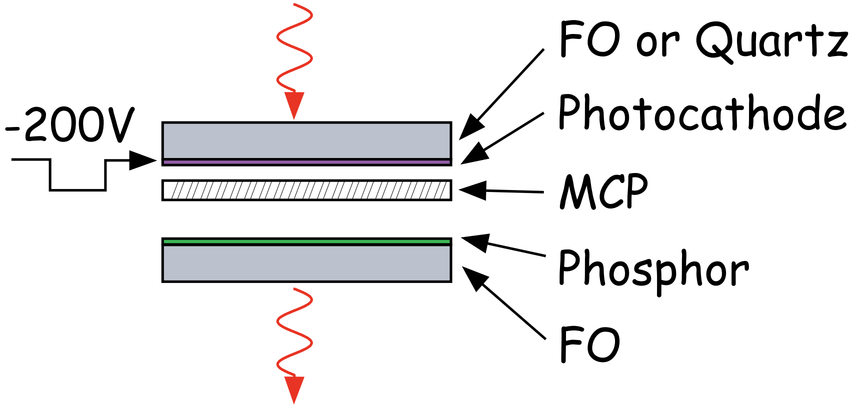
GEN2 onwards Technology

Based upon gated proximity focussed tubes.

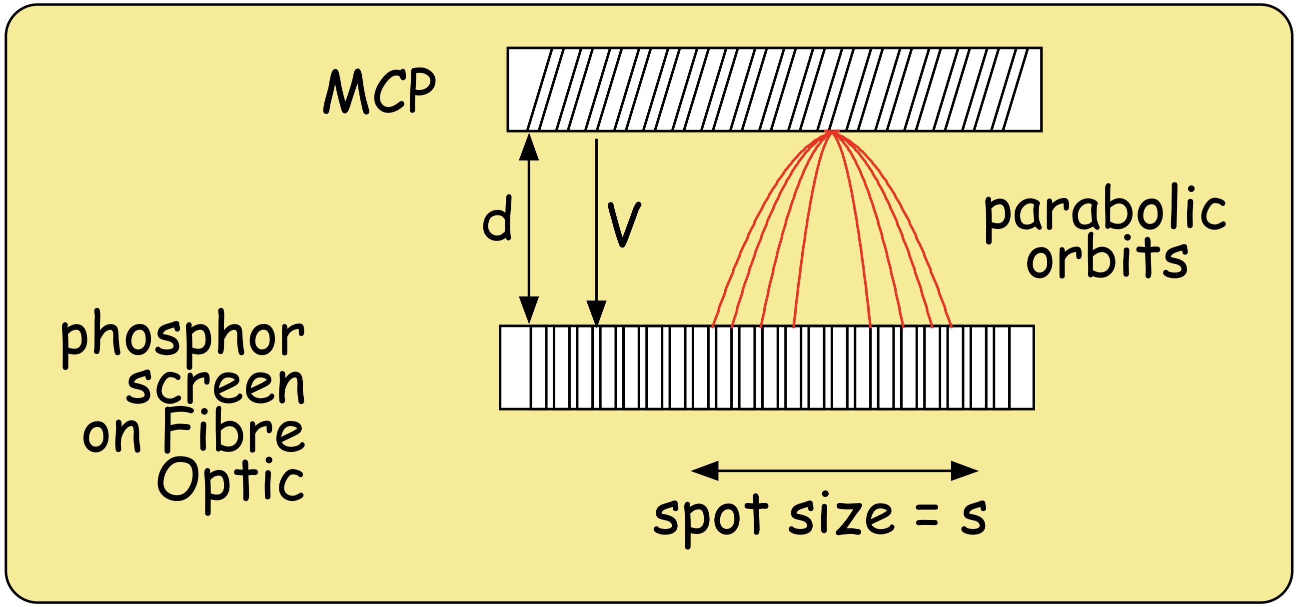
GEN3 Semiconductor cathodes. These need more gate volts to overcome barrier layer. Have good IR response. The newest from Hamamatsu have no barrier

Extinction ratio

> 10^7 for red light. Drops off in the UV due to direct excitation of MCP



Diversion: Proximity Focussing



For V=4kV, d=500μm

and the typical energy of an electron = 10eV

This gives ~90μm.

However, the electrons come out at a restricted range of angles so the resolution is typically 4 to 5 times this figure

Diversion: Vacuum Transfer Technology

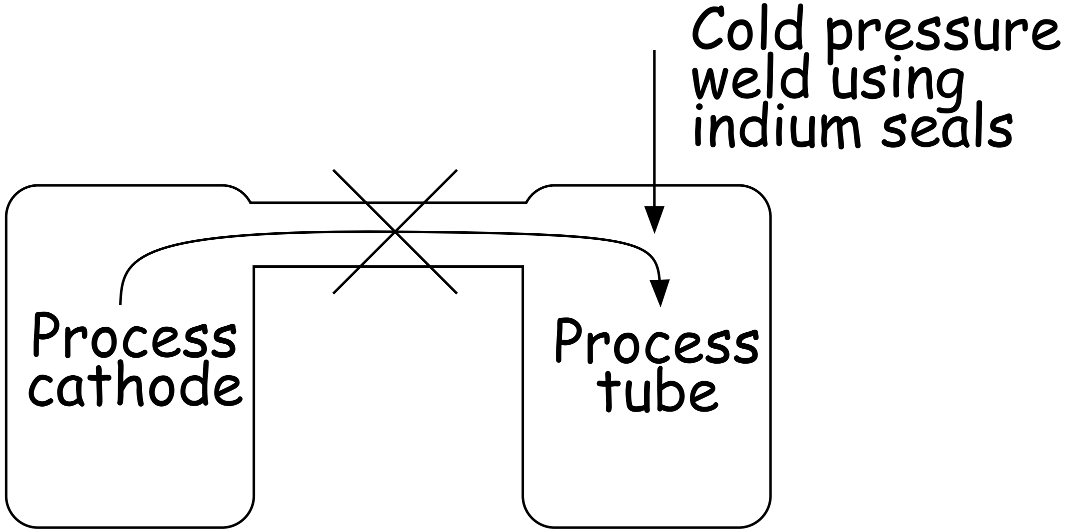


Image Detection and Recording,

Lens v. Fibre optic coupling

Fibre Optics

Low distortion, resolution down to around 5μm, collecting efficiency better than f/1.

Soft surface, surface is image plane so cleanliness is imperative.

Good contact needed, resolution ~ element separation above 5μm.

Lenses

Some distortion, collecting efficiencies better than f/1, resolution down to 1μm but not at f/1. Can image through windows.

Demagnification

FO tapers compact, but no more efficient than a good lens.

Image convertor coupling

FO input, Photocathode with QE of ~10%, gain. Can demagnify large amounts with an increase in brightness. 80 line pairs/mm available at the output.

Image Detection and Recording,

Charge Coupled Detectors, CCD

QE, Sensitivity, Noise, Dark current

QE around 70 to 80%.

Digitisation noise a concern as is dark current.

Cool the chip and if possible the digitiser.

Watch out for condensation problems with a cooled system.

In a FO system contact must be maintained. It can be lost during cooling.

Pixels size

Match pixel size to required resolution.

If you have more pixels than needed it is better to bin before digitising.

For a 40mm intensifier format one can get 4k square chips.

For streak tubes with low resolution a 1k square chip will be adequate.

Back thinned CCD

Direct excitation of charge wells, excellent resolution, less blooming.

Needs higher energy electrons to penetrate back of CCD. excellent choice for streak cameras with 15keV electrons.

Need to match streak camera format to chip.

Next generation of Streak cameras

Objectives

1. Larger format, more data throughput
2. Higher time resolution

Larger format

To overcome space charge at the lens cross over point use anamorphotic electron lens → quadrapole. Needs a lot of potentials to be set accurately.

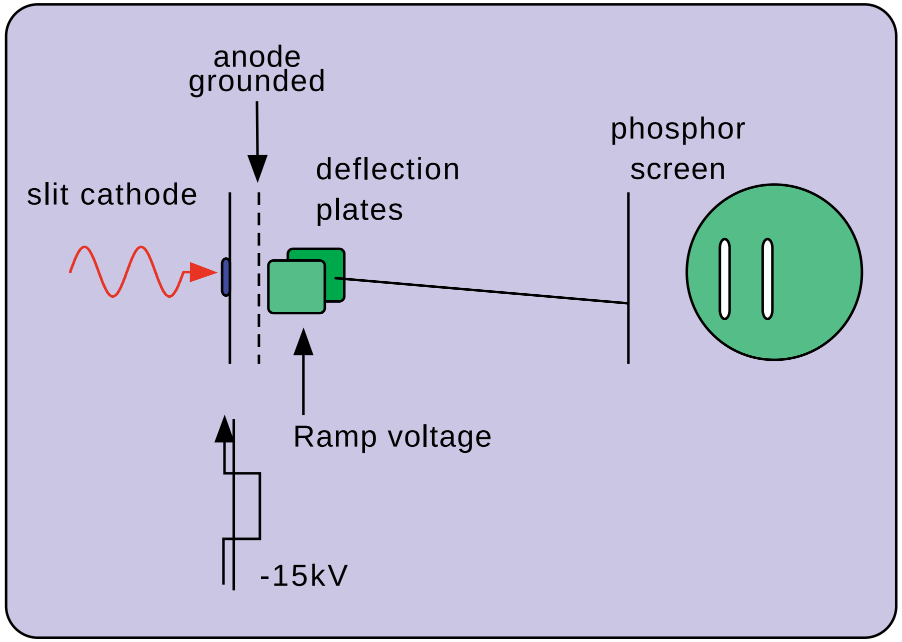
Higher time resolution

Need to reduce time spread of photoelectrons.

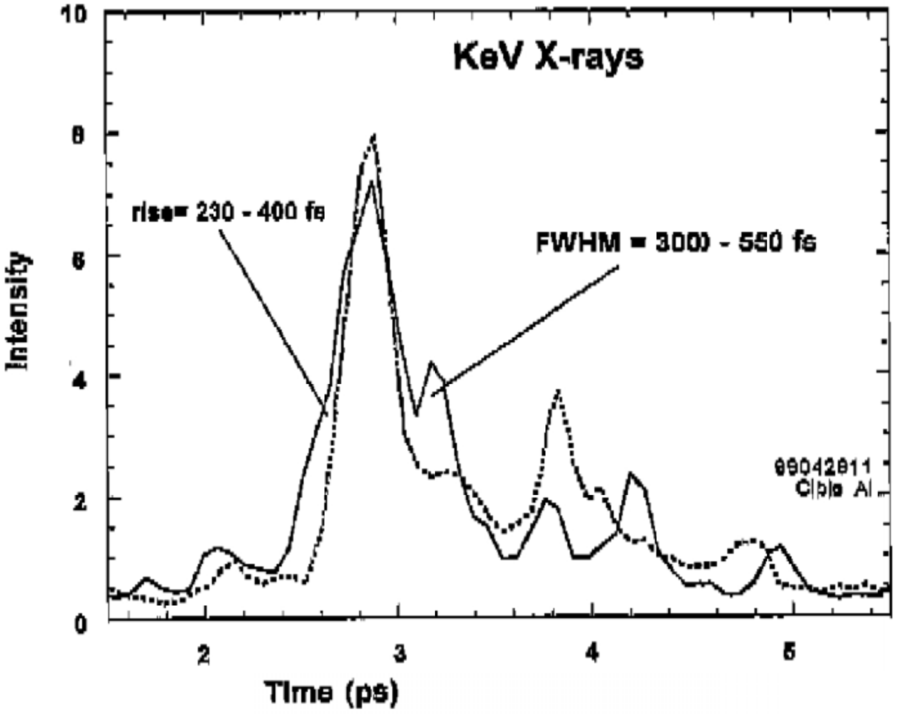
1. Magnetic focussing, non dispersive. Hamamatsu, Japan
2. Proximity focussing, needs very high extraction voltage. J-C Keiffer, NRC
3. Bilamellar tube, energy selection, lower sensitivity. Photonis +Axis Photonique
   Also uses quadrapole lens technology.

Sub Picosecond Streak Cameras

A proximity focussed X-ray streak camera using a pulsed cathode and extraction grid.



PX1 camera coupled to the Kentech cathodee pulser.

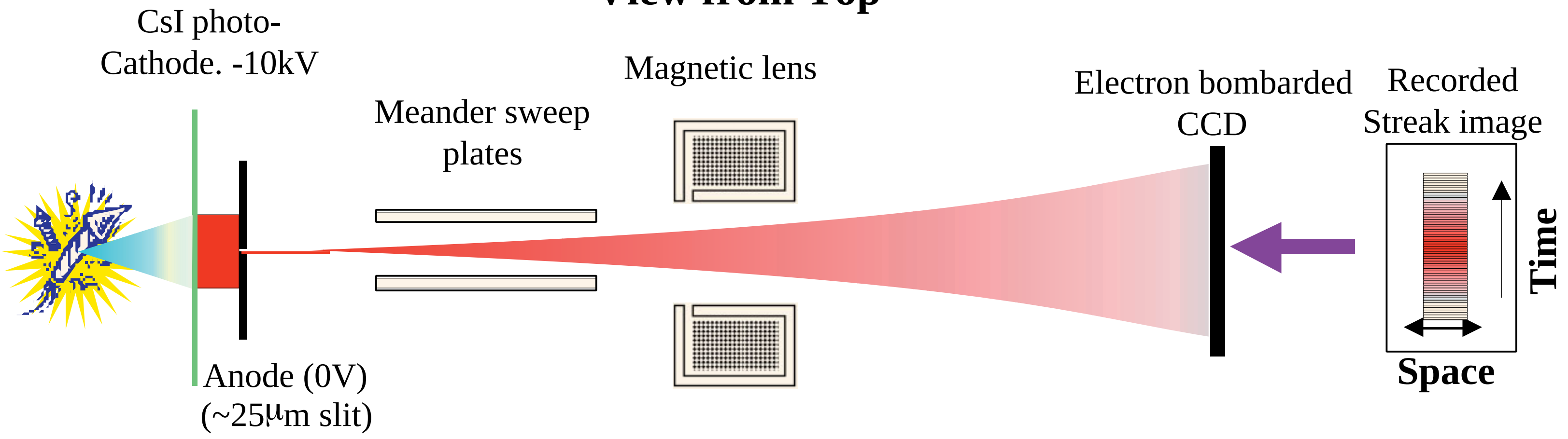


P. Gallant, Z. Jiang, J.C. Kieffer, INRS
19993, April 29

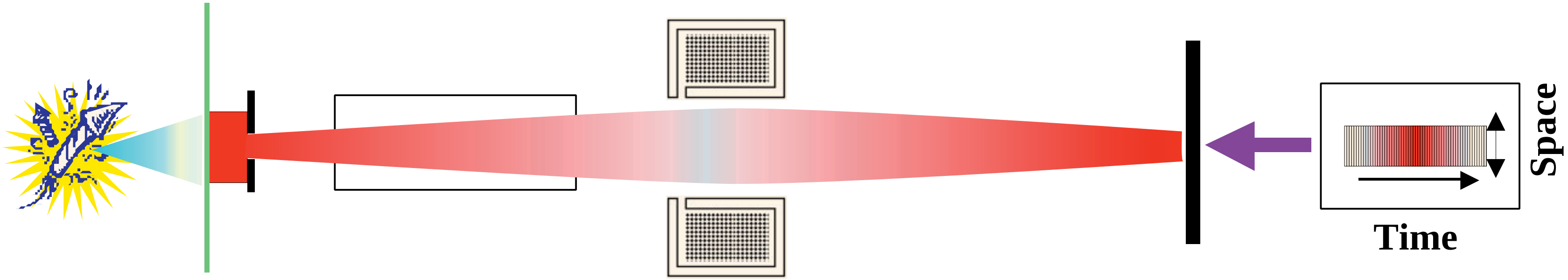
Some results taken with a streak tube used with a photocathode pulser.

Ultrafast Sub Picosecond Streak Camera
University of California at Berkeley

View from Top



View from side



New Section
Gated Imagers

Gated Imagers

Technology

Based upon gated proximity focussed tubes.

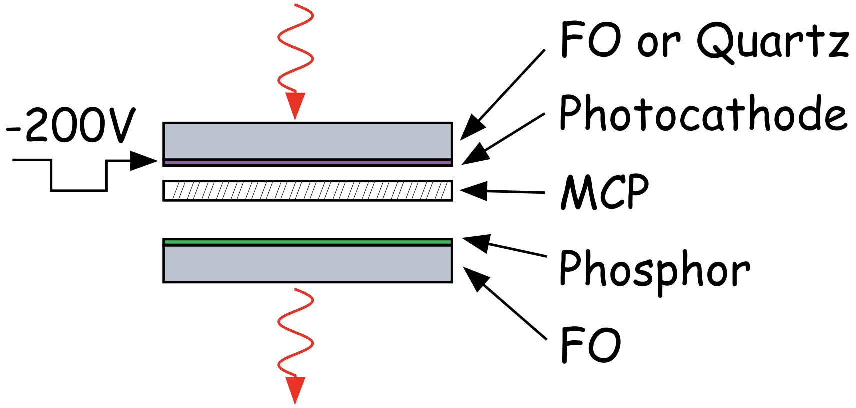
Optical gate the cathode

Cathodes S1, S20, S25, GEN3

GEN3 These need more gate volts to overcome barrier layer. Have good IR response

Optical

Gate voltage of a few volts will turn the tube on/off but ~ 100 volts for good spatial resolution to maintain proximity focussing. Rep. rates to 200MHz.



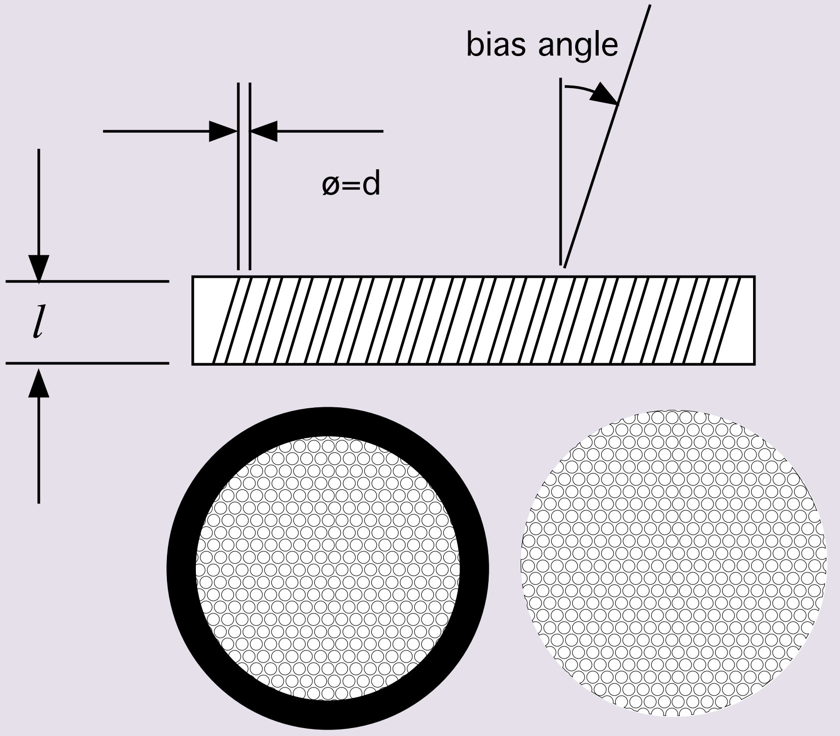
Extinction ratio

> 10^7 for red light. Drops off in the UV due to direct excitation of MCP

Minimum Gate width

Limited by RC diffusion of charge. R is set by the cathode resistivity, C by the cathode to MCP gap.

Diversion: Microchannel Plates

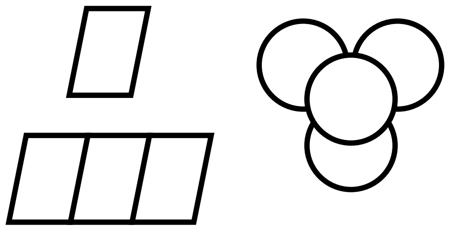


Hard edge
more robust
Will bow it if absorbs moisture.
Dielectric discontinuity

Soft edge
more fragile.
Will not bow so easily.
Constant effective dielectric

effective ~ 3.5 for a 200μm plate and 4 for a 500μm plate

$\frac{l}{d}$ is a measure of the number of electron cascade stages.
The gain at a given voltage is a function of l/d as is the transit time.



For High gain use two plates but separate them so that one channel in the first feeds several in the second.

Standard plates are 500μm thick with l/d =40
200μm plates are used in some fast cameras. These are very expensive.

Capacitive Gating in Optical Gated Imagers

Technology

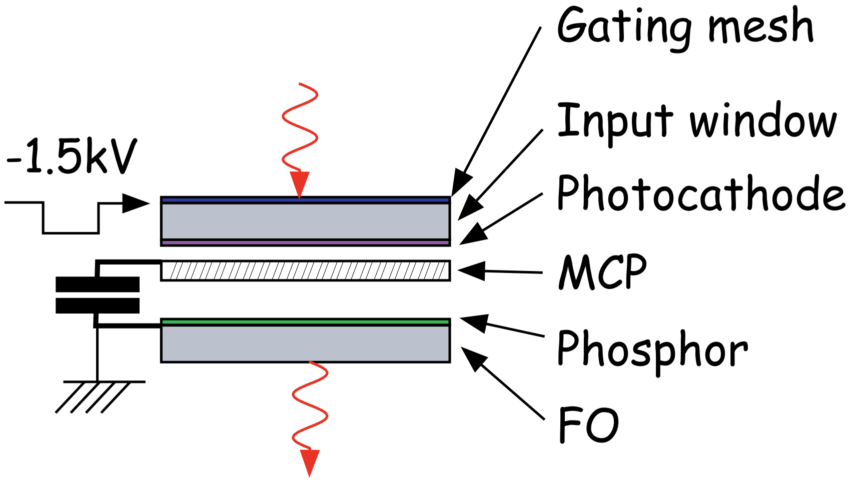
Based upon gated proximity focussed tubes with no fast connection to cathode

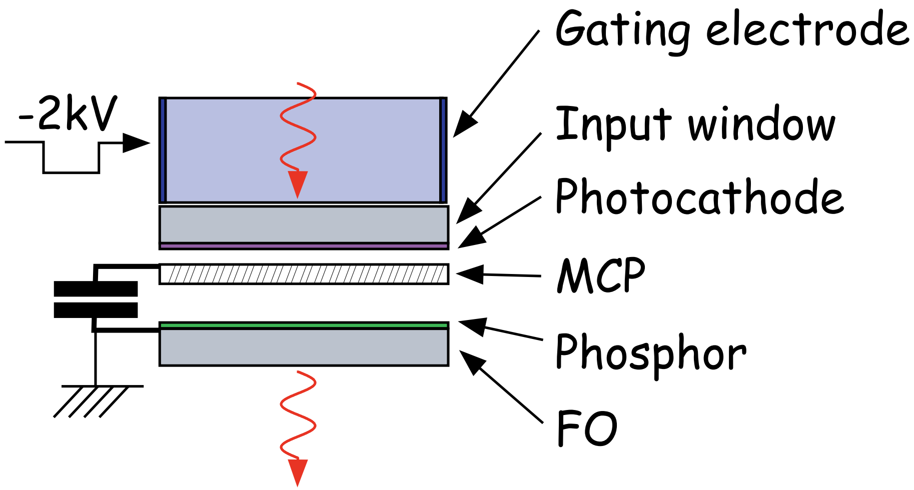
Cathodes S1, S20, S25

Optical gate the cathode

Gate Technique

Put the whole tube in a gated electric field. Capacitively couple the MCP input to ground. Rep. rates to 10kHz





Minimum Gate width

Limited by driver technology to around 50ps.

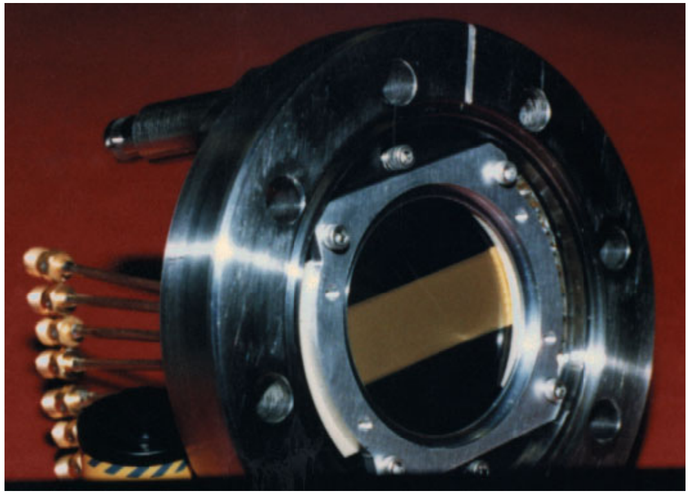
X-ray Gated Imagers

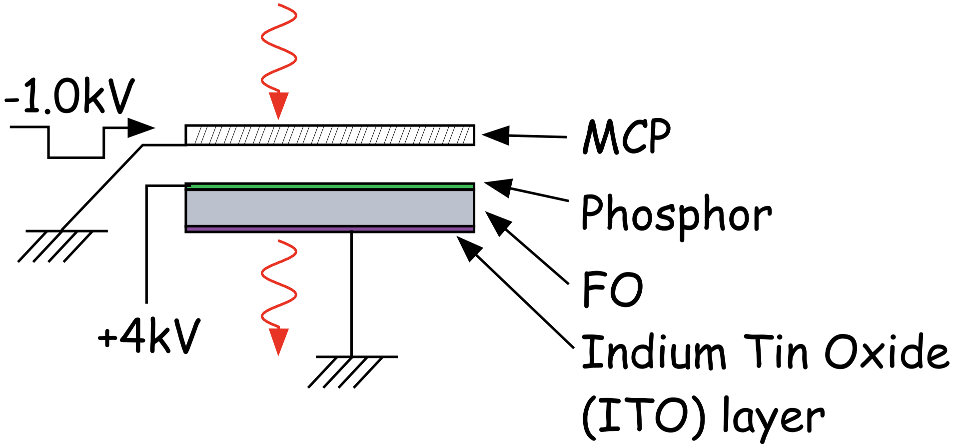
Gate Technique

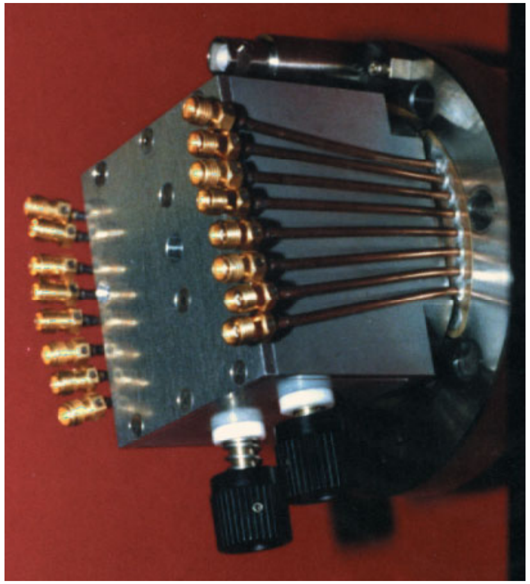
Gate the MCP, use stripline geometry.

Gate voltage around 1kV.

Devices are not normally sealed.







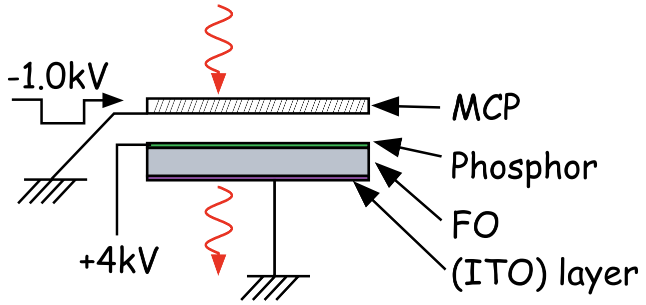
X-ray Gated Stripline Imagers

MCP Stripline

$\varepsilon_r \sim 4$

An 8mm wide strip on a 500µm thick plate is around 6Ω, on a 200µm strip it is around 2.5Ω Gate voltage is around 1kV.

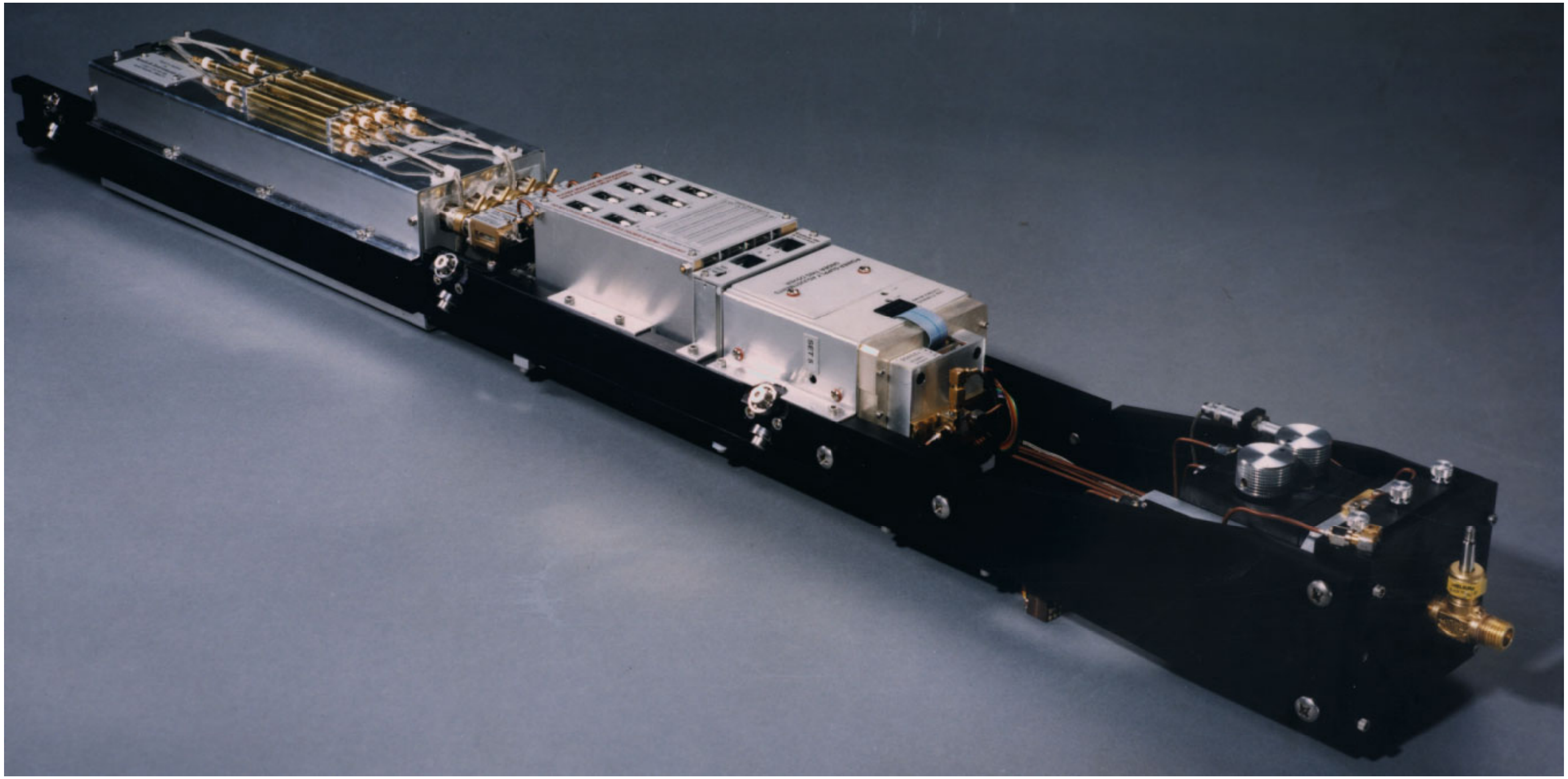
Peak gate power is 21kW per mm wide @500µm and 50kW per mm wide @200µm



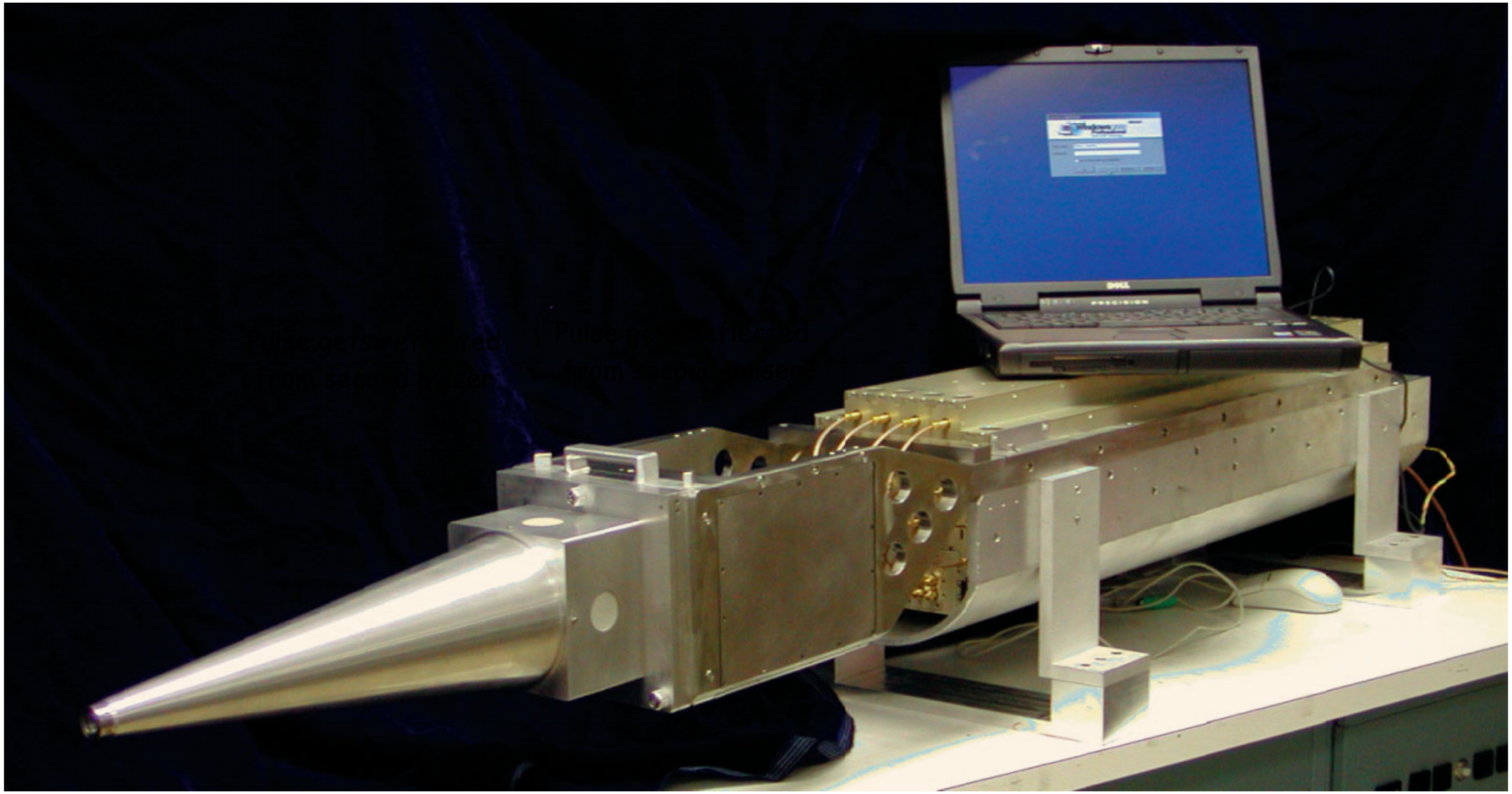
Gate drive electronics

- Nearly all made by Kentech
- Typically use one 1MW card for each 8mm strip.
- Pulse power is wasted getting the pulse shape and impedance conversion
- Pulses can be 4kV, 100ps fwhm, into 50Ω

A typical X-ray Gated Stripline Imager

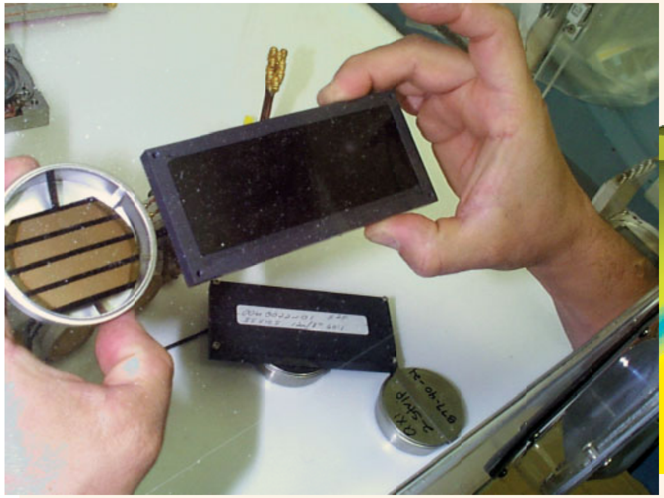


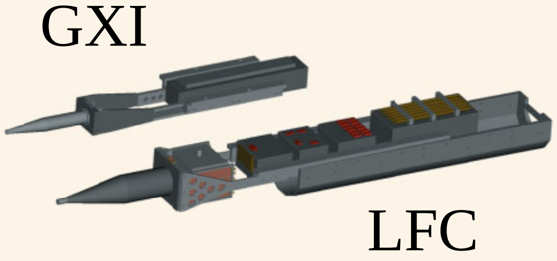
The Los Alamos Large Format Camera

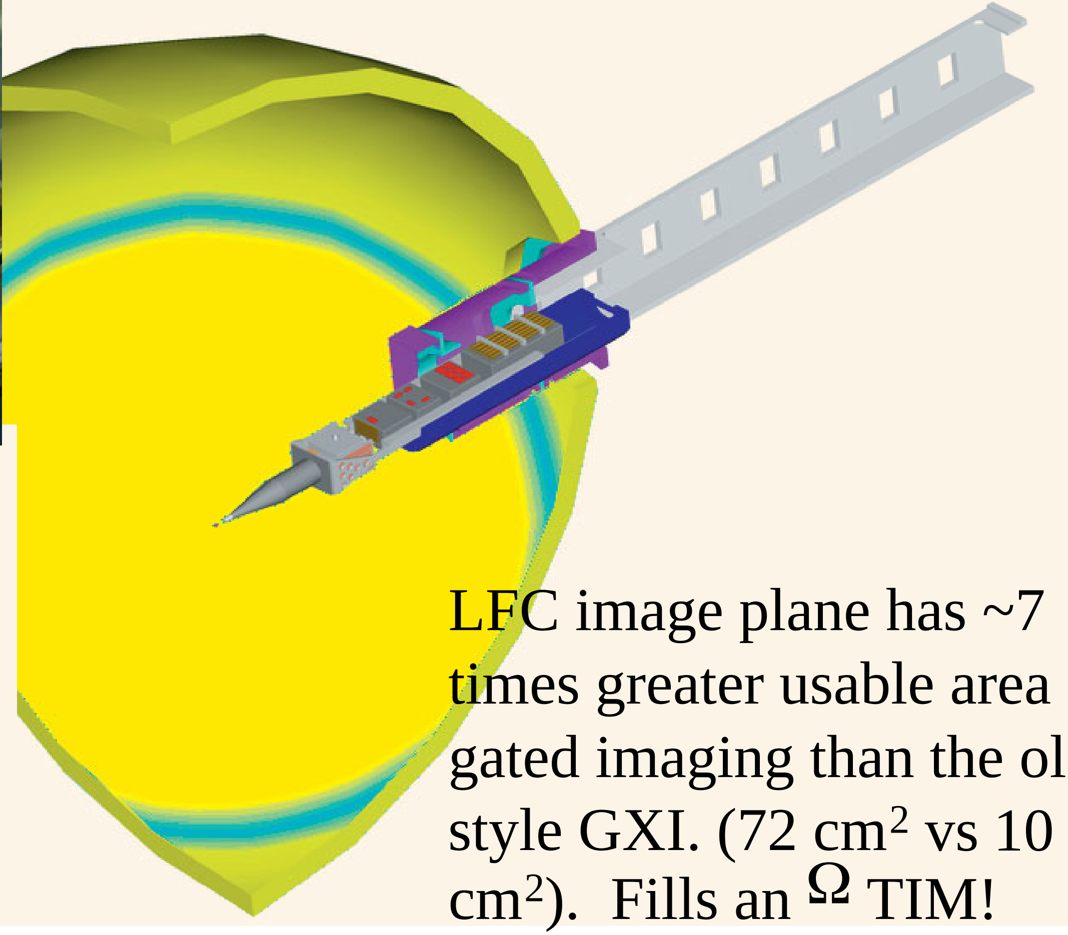


The Los Alamos Large Format Camera

std 40 mm vs 1 of 3, 100 x 35 mm MCPs

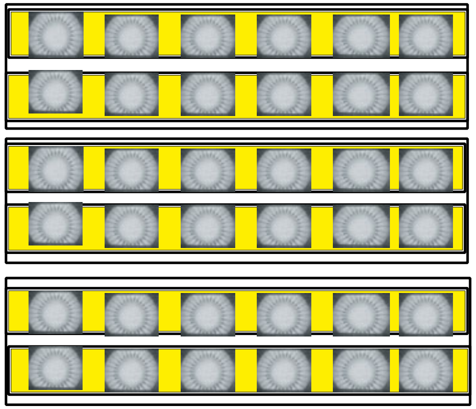


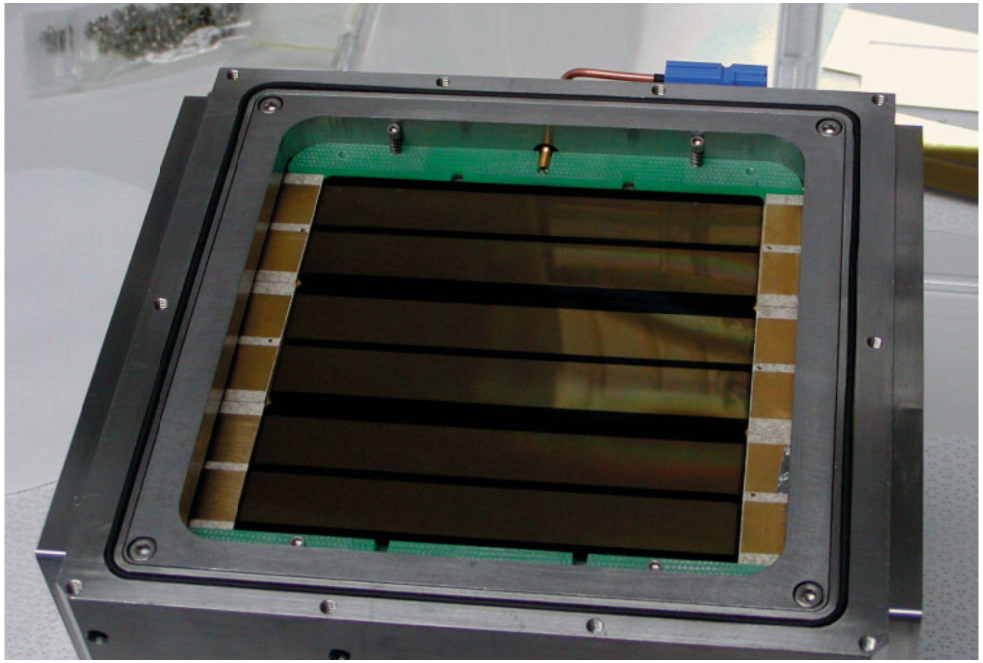




LFC image plane has ~7 times greater usable area for gated imaging than the old style GXI. (72 cm^2 vs 10 cm^2). Fills an Ω TIM!

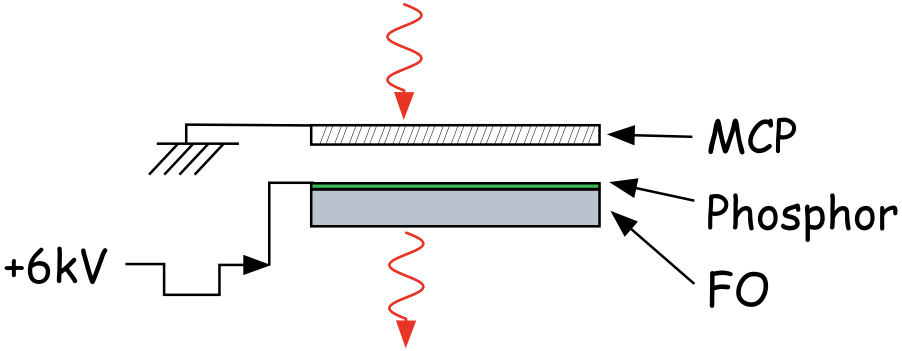
The Los Alamos Large Format Camera MCP, DC and gated (120ps) shots





Continuous temporal coverage of 4.1 ns (~680 ps/_strip)
6 images/microstrip X 6 microstrips = 36 data points

Other Gated X-ray Imagers



Gate Technique

Gate the MCP and phosphor together.

gain set by changing the MCP to phosphor spacing.

Very hardy in bad vacuum environments.

Need 6kV gate pulses but the capacitance is lower by around 5 times.

Gate drivers are usually spark gaps → jitter and timing problems.

Good for few ns regime.

New Section
High rate Imagers

High Rate Imagers

Recently developed Optical gated imagers can achieve 110MHz gating rate.
The average power from a typical mode locker laser oscillator is similar to that from a pulse picked and regen. amplified system.
High rate imagers can offer similar single to noise levels for some experiments with much less complexity.
Applications range from Fluorescence Lifetime Imaging (FLIM), imaging through turgid media.

Fluorescence Lifetime Imaging

Measure surface chemistry remotely and with high precision and spatial resolution. Applications to medical diagnosis and the semiconductor industry.

Combined with laser etching it can offer ways to clean surfaces very carefully or remove layers of a coating.

Fluorescence Lifetime Imaging

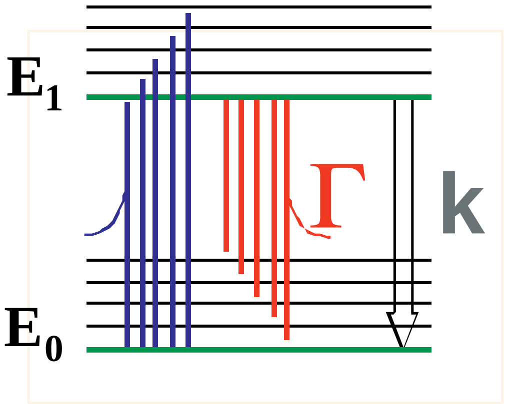
Techniques:-

1 Gated imager
2 Sinusoidally modulated detector/source Phase measurement.
3 Streak camera

1 Simple wasteful of light as ungated signal is lost.
2 sinusoidal source and detector are not easy to achieve. Single point detector and source can be very efficient. Long time to acquire image.
3 Only one spatial dimension, second achieved with scanning. Continuous recording, efficient, high capital cost

Imaging tissue with fluorescence

Aim: to detect or image different types of tissue or states of tissue using optical radiation to achieve ***contrast***



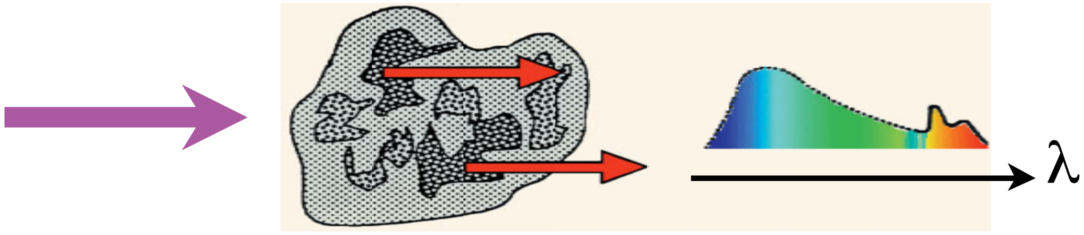
Intensity **~ f{**η**},** $\eta = \Gamma/(\Gamma+k)$

Wavelength, $\lambda \sim hc/(E_1-E_0)$

Lifetime, $\tau = 1/(\Gamma+k)$

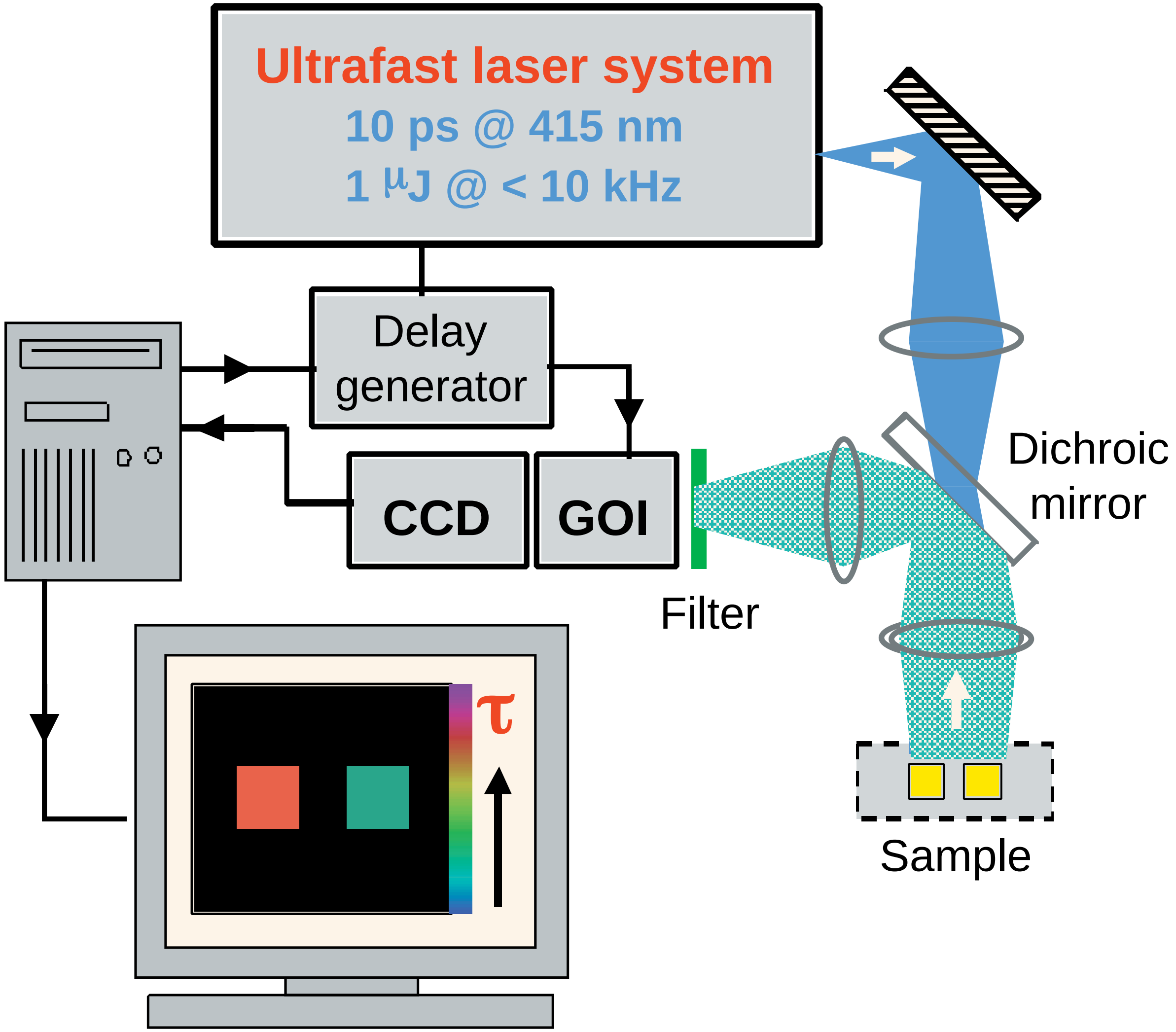
Problems: *heterogeneity, scattering and background fluorescence*

Difficult to make absolute intensity measurements



Solution**: image** τ – *a* ***relative*** *measurement*

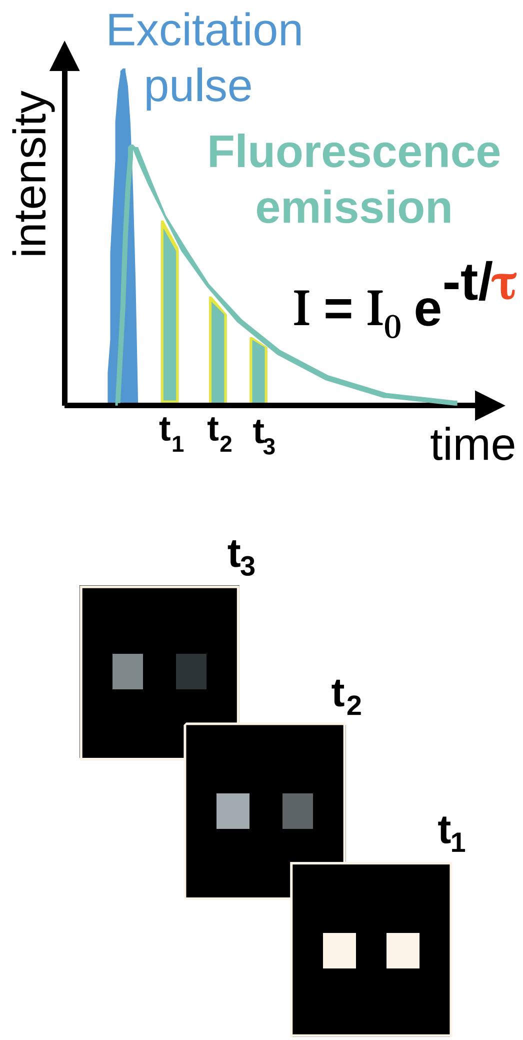
Fluorescence lifetime imaging (FLIM)



Ultrafast laser system

10 ps @ 415 nm

1 μJ @ < 10 kHz



$$I = I_0 \, e^{-t/\tau}$$

Ultrafast technology for wide-field FLIM

Sources

Home-built diode-pumped Cr:LiSAF oscillator-amplifier

10 ps @ 10 kHz

~ 100 μW @415 nm

+

GOI

~ 70 ps gate width

Up to 10 kHz rep. rate

or

Commercial Ti:sapphire femtosecond oscillator

100 fs, 80 MHz, 10 mW, 415 nm

Commercial picosecond diode laser

40 ps, 40 MHz, 1 mW, 400 nm

+

HRI

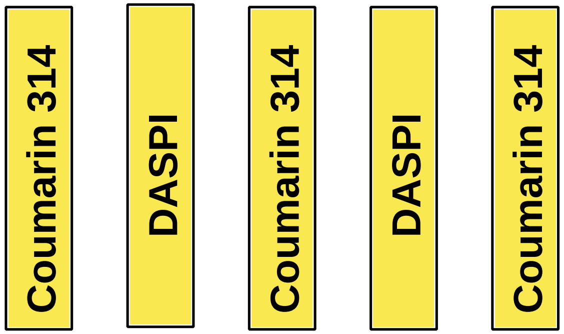
~ 250 ps gate width

~ 50 – 1000 MHz rep. rate

Detectors

FLIM of dye samples: chemically specific imaging

Dye samples:



Coumarin 314

DASPI

Coumarin 314

DASPI

Coumarin 314

Fluorescence lifetime map:

$$\tau = f\{\Gamma\}$$

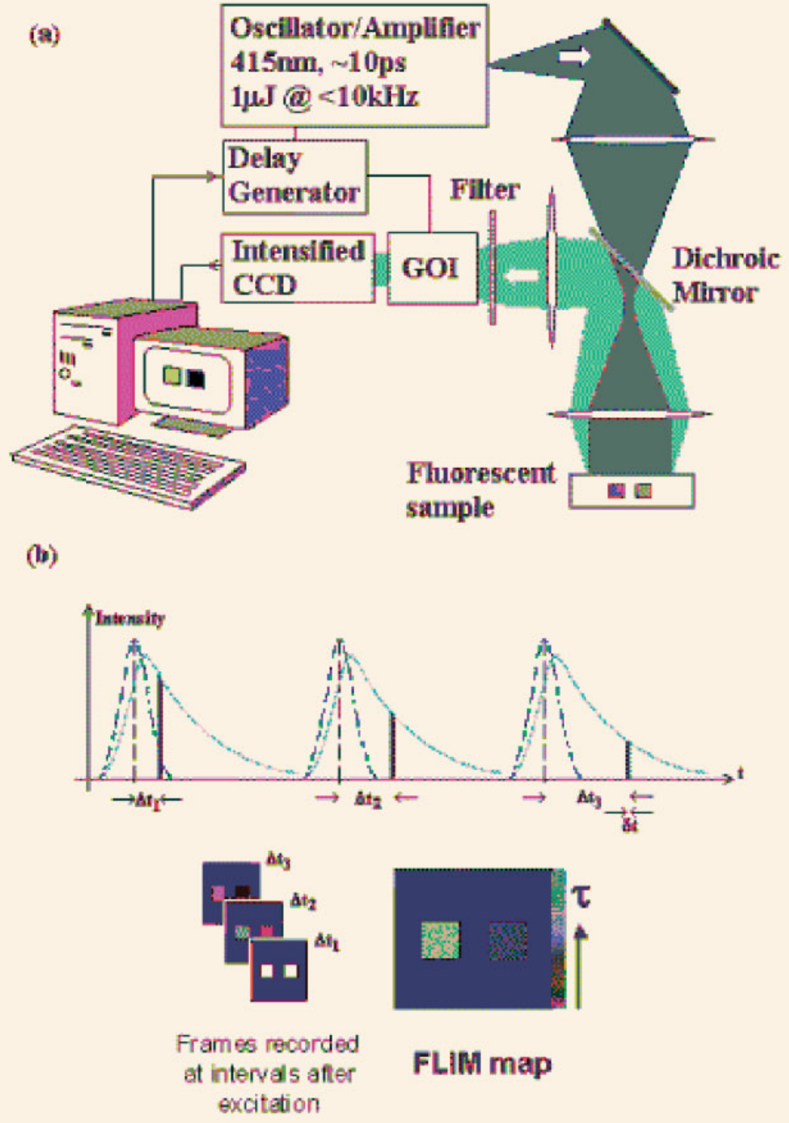
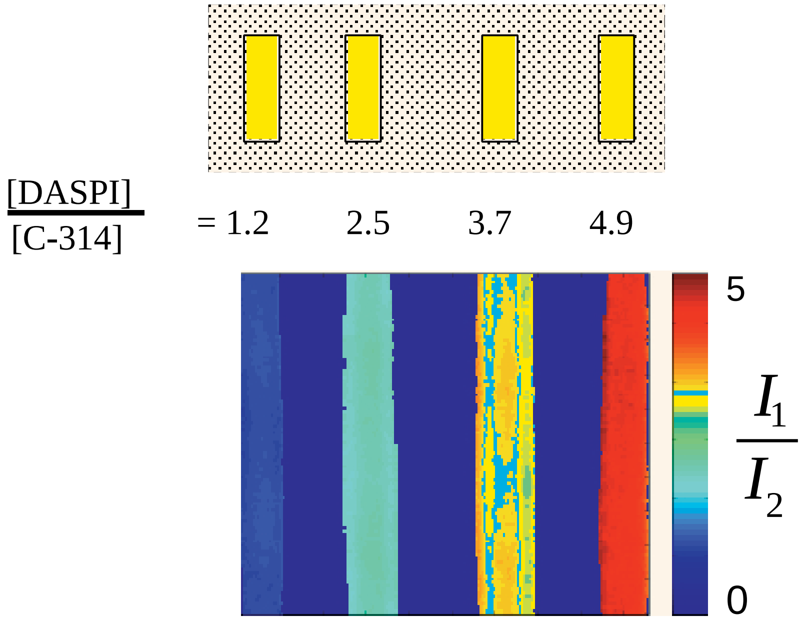


Figure 1. (a) Schematic of experimental FLIM system and (b) the acquisition process

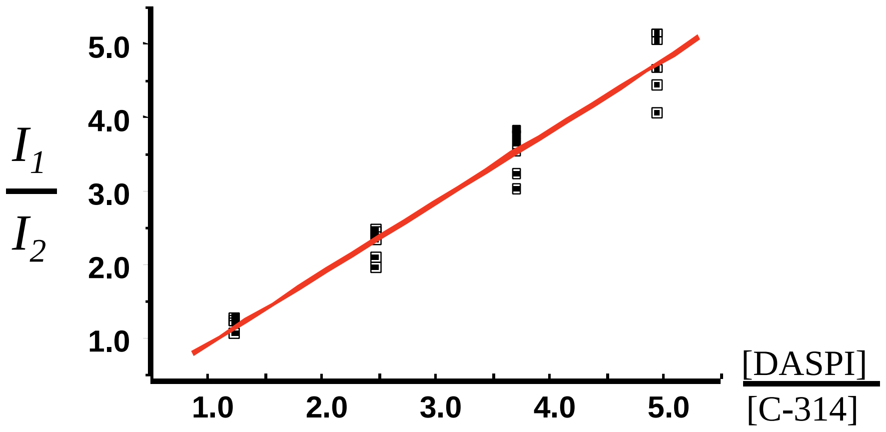
Quantitative whole-field FLIM of [fluorophore] ratio

Pipettes with dye mixtures



Two component decay:

$$I(t) = I_1 e^{\frac{-t}{\tau_1}} + I_2 e^{\frac{-t}{\tau_2}}$$

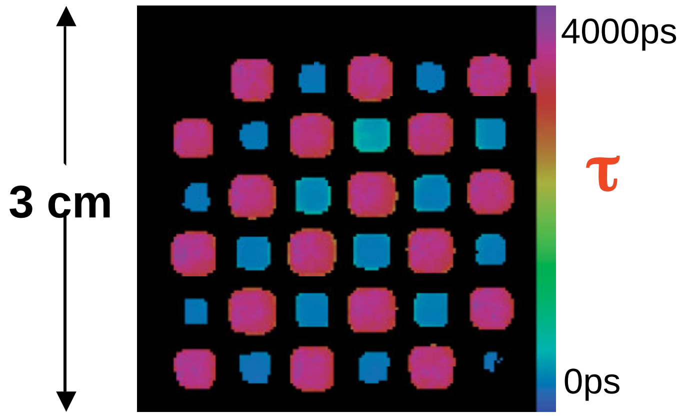


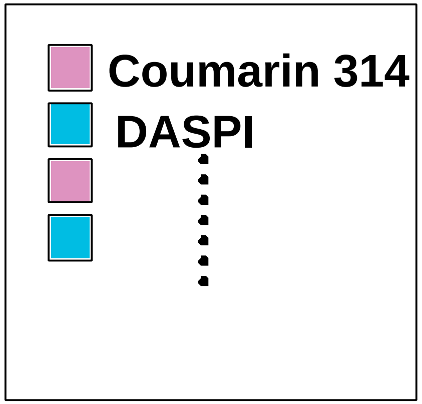
Quantitative high-speed assays

e.g. bio-chips, HTS, DNA sequencing…

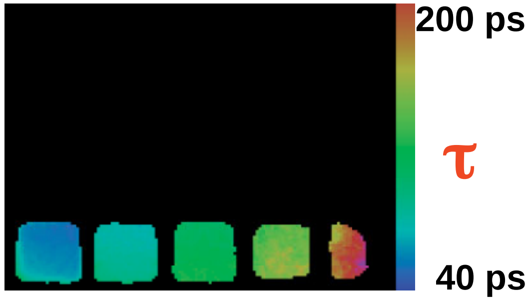
Macroscopic multi-well-plate imaging – for assays

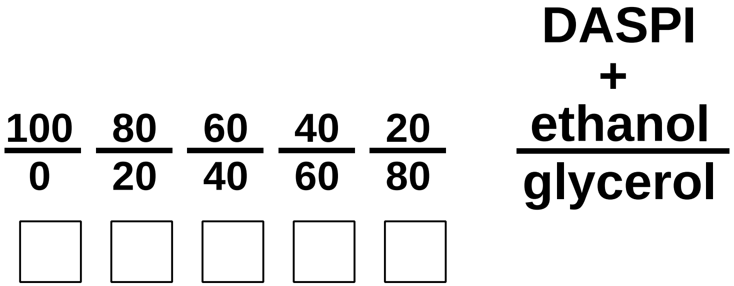
Chemically specific imaging





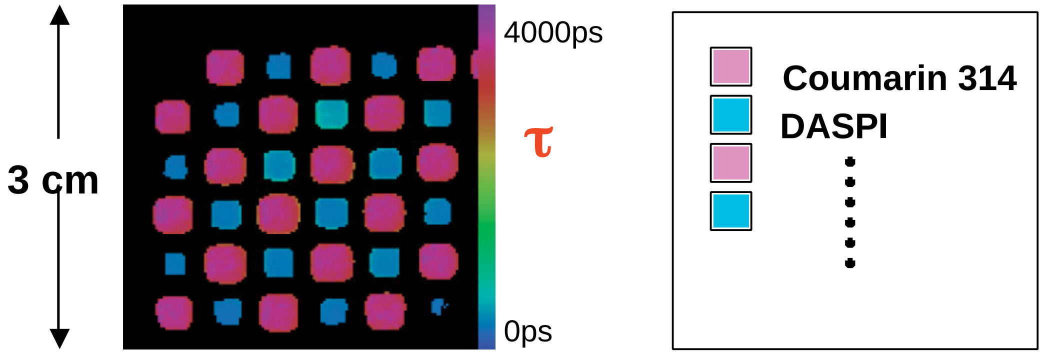
Influence of the fluorophore environment (viscosity)





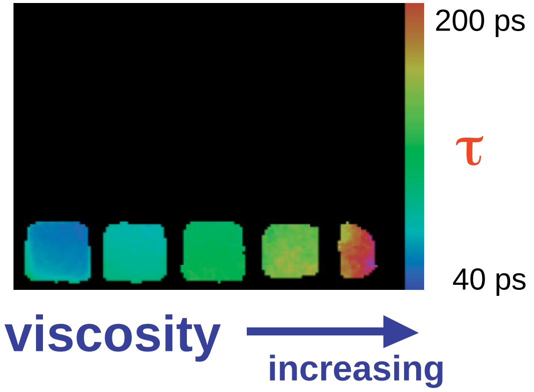
Macroscopic multi-well-plate imaging – for assays

Chemically specific imaging

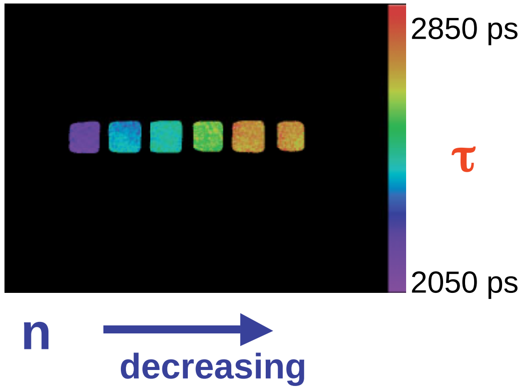


Influence of the fluorophore environment (viscosity)

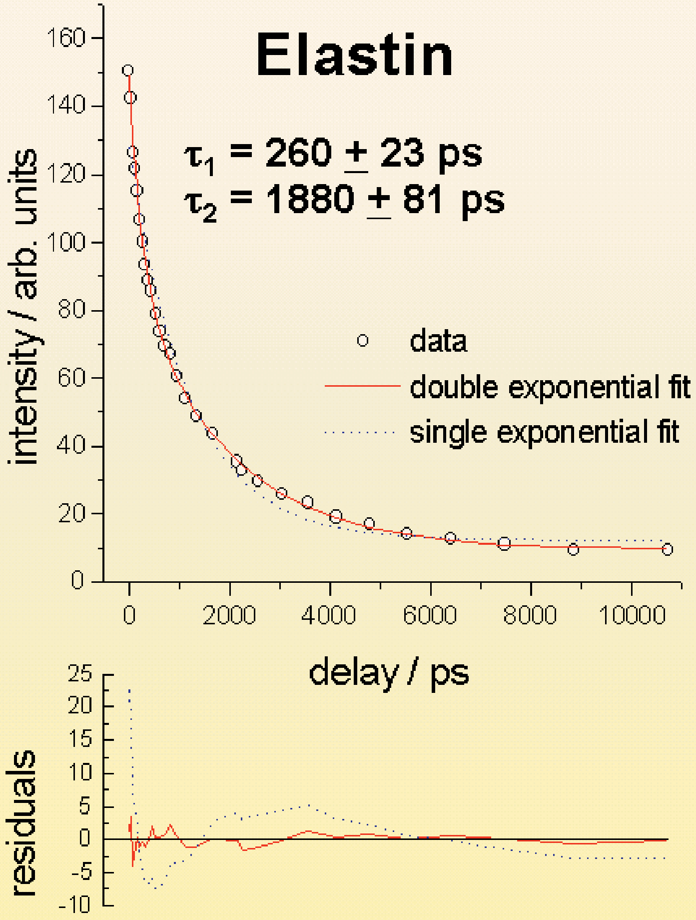
DASPI in ethanol/glycerol



E-GFP in glycerol/buffer solution



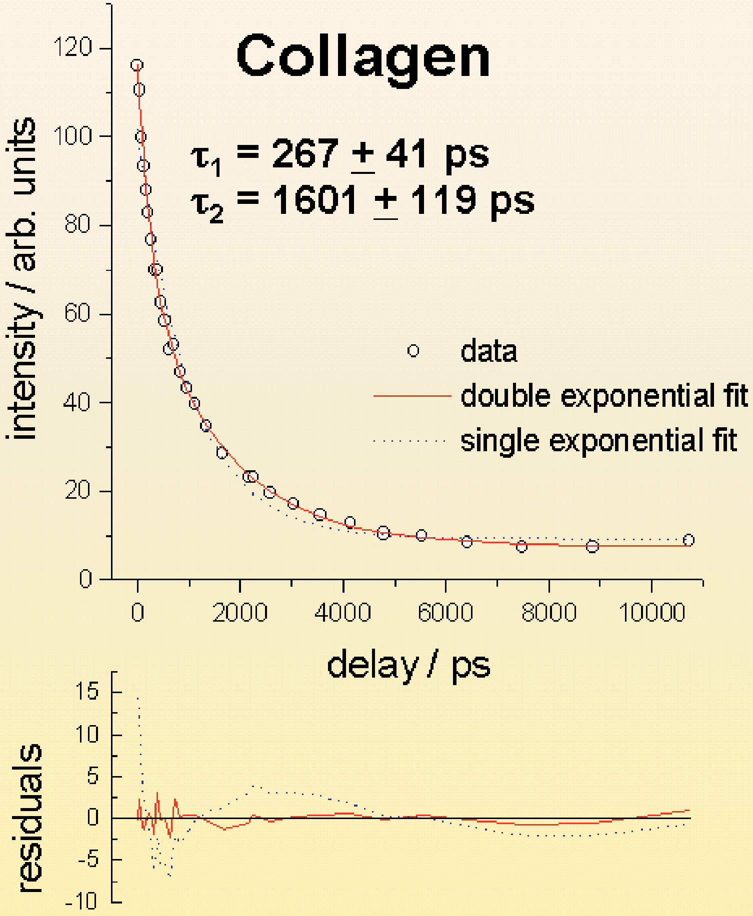
Time-resolved autofluorescence, 415nm excitation



Elastin

τ_1 = 260 ± 23 ps

τ_2 = 1880 ± 81 ps



Collagen

τ_1 = 267 ± 41 ps

τ_2 = 1601 ± 119 ps

Application of stretched exponentials to FLIM: 4260-12 (Wed 13:50)

Lifetime contrast? ☑

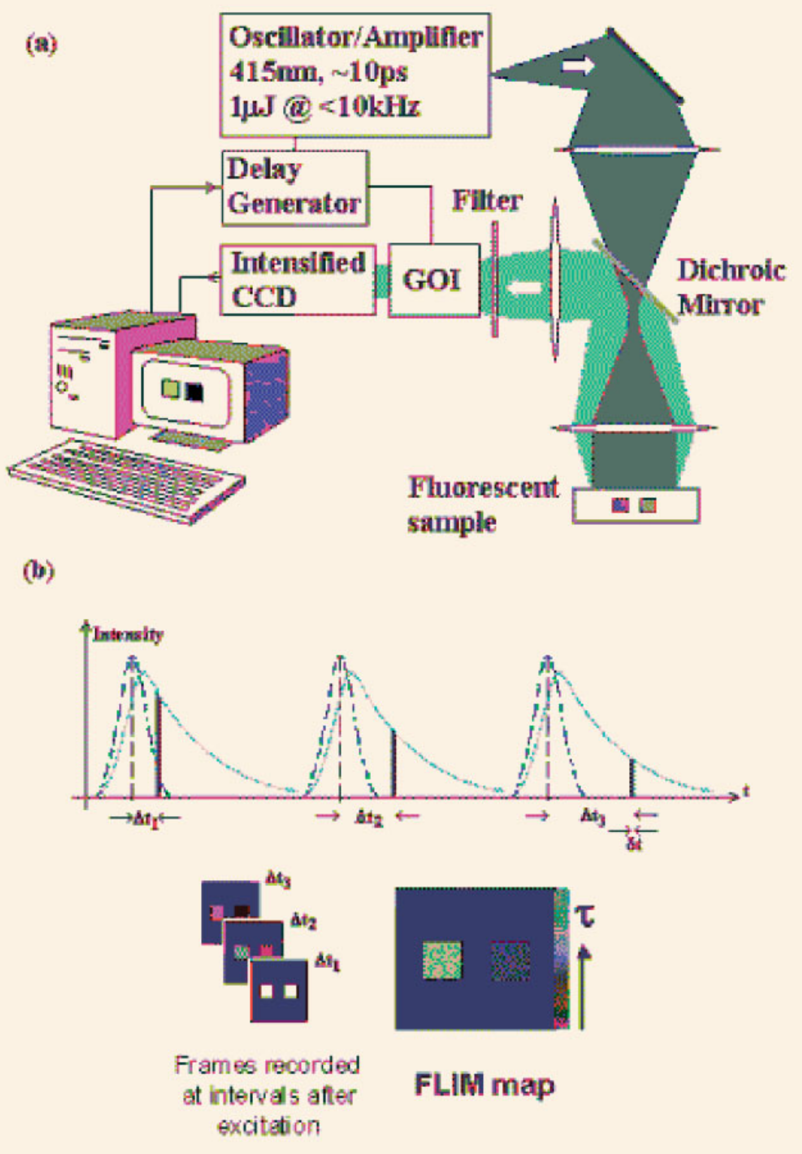
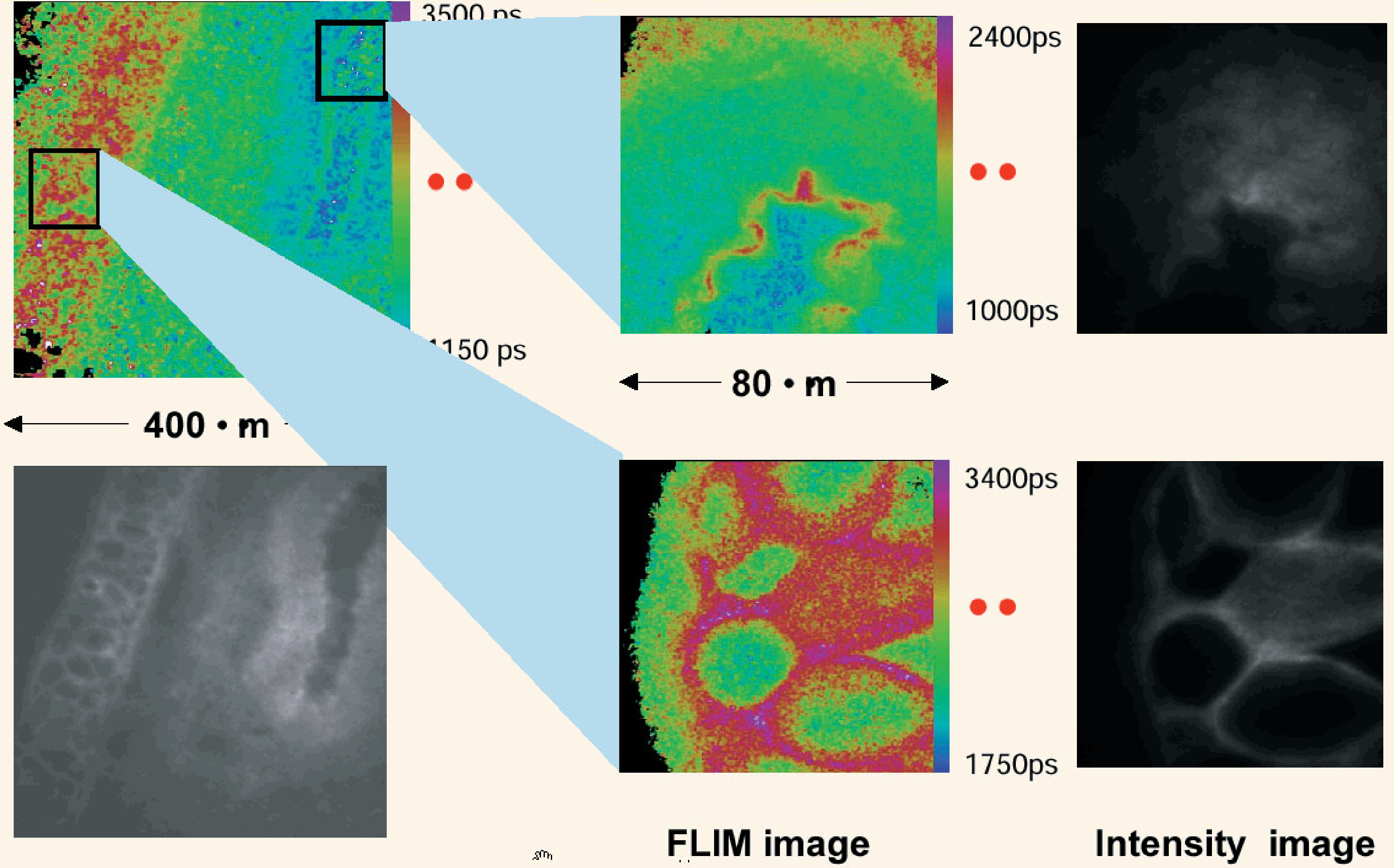


Figure 1. (a) Schematic of experimental FLIM system and (b) the acquisition process

Microscopic imaging of cartilage and artery



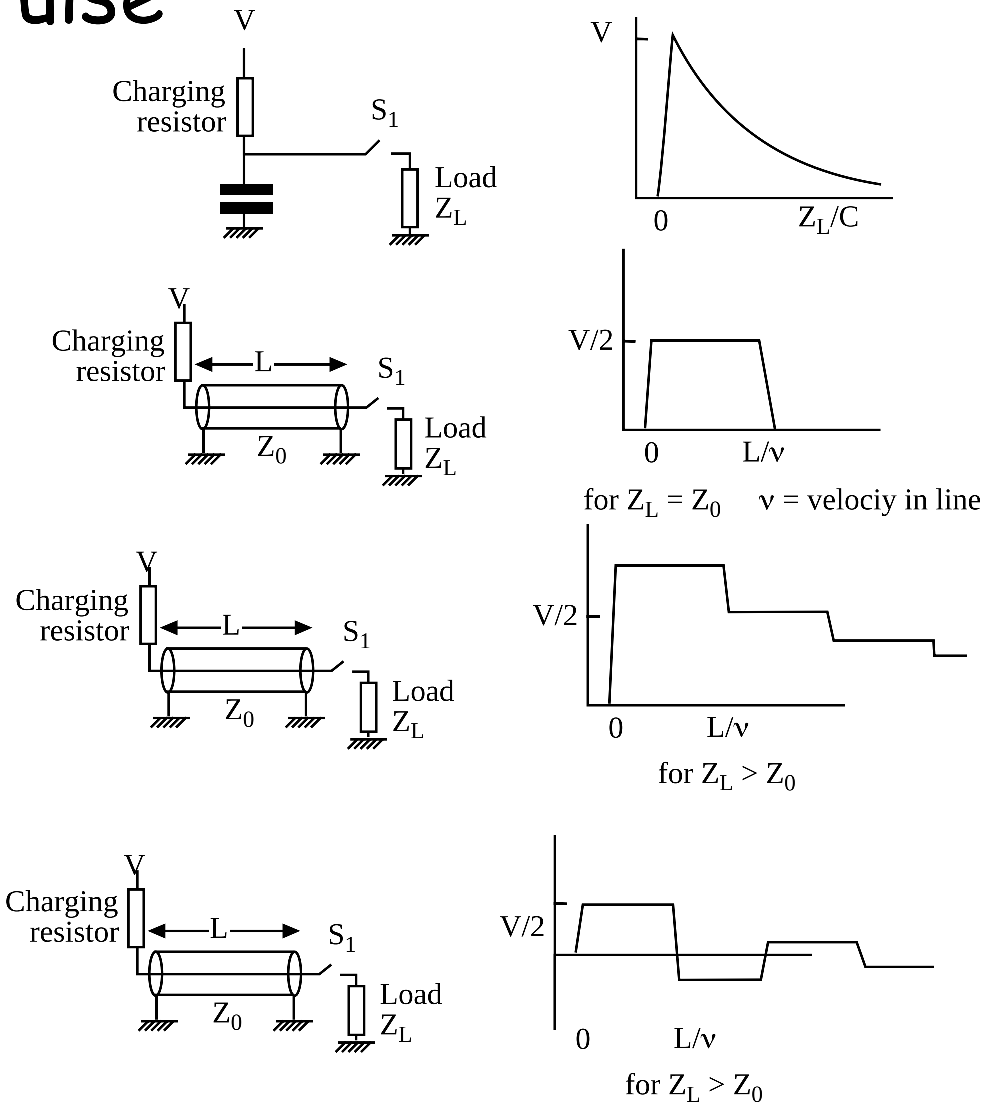
New Section
Pulse Generators

An Introduction into Pulse Generators

Pulse forming circuits.

All rely on switching a storage device into a load. Pulse shapes depend upon the configuration

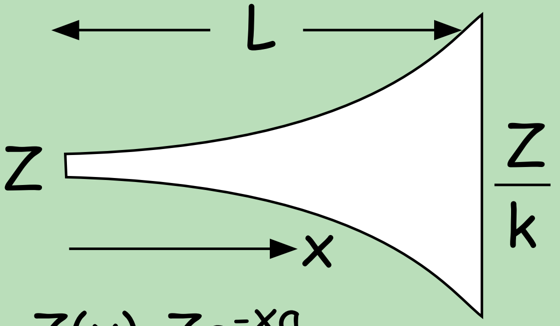
Output amplitude = half the charging voltage in simple configurations



http://www.kentech.co.uk/transmission_lines/Transmission_lines.html

Impedance Transformers

Z into Z/k where "k" is any number.

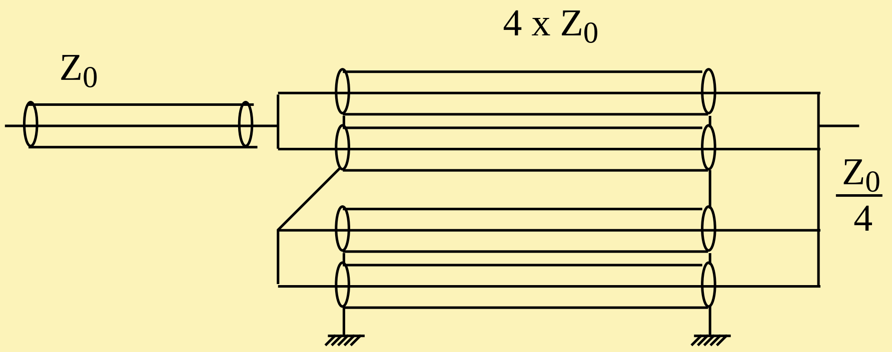


$Z(x)=Ze^{-xa}$

Good for $\tau_r \ll L\varepsilon_r/c$

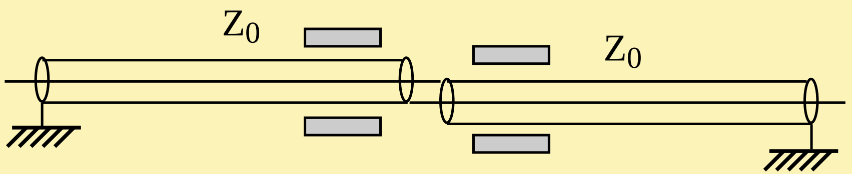
i.e. low frequencies are not transformed

Z into Z/n where "n" is a perfect square.



two in series by two in parallel

Pulse inverting circuit



ferite beads

Switch Technologies

Ideal switch would have a zero on impedance, infinite voltage hold off, and be triggerable with zero jitter on command at and repetition rate. In addition it would turn off on command.

Vacuum switches

- Thermionic valves, spark gap
- Low lifetime at high power. Spark gaps have jitter, risetime limitation

Gas switches

- Krytron, Thyratron, Ignitron, spark gap. Jitter, ageing, risetime limitation

Liquid switches

- Spark gap, jitter but can have good lifetime and very high rep. rate if the liquid is flowed. Risetime can be well sub ns.

Switch Technologies

Solid state switches

Spark gaps are single shot and then replace the material.

Semiconductor Switches Avalanche

Low power but can have very low jitter (~1ps),

Long lifetime > 10^{10} shots

High on resistance in avalanche mode

Can be cascaded in series and parallel for high power.

Large stacks can run at 10kHz. Single devices at 100kHz.

Risetime can be sub 100ps. Limited charge transfer.

Semiconductor Switches Field Effect transistors

Not as fast as avalanche transistors, ~ 1ns risetime

Can be turned off with care. Will run at many MHz.

cannot switch as much power but can handle large mounts of charge.

New Section
Pockels Cells

Pockels Cells

Principle

Electrically induced bifringence.

Used for changing the polarisation of light.

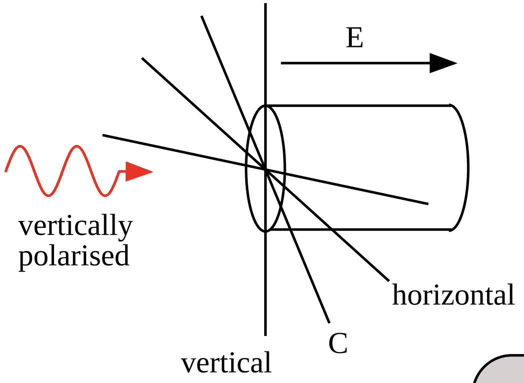
Usually, linear ⇔ circular or linear ⇔ orthogonal

Pockels cells do not "rotate" the plane of polarisation.

There is no intermediate state with light polarised at 45°.

This is unlike a Faraday rotator.

The states are linear ⇔ elliptical ⇔ circular ⇔ elliptical ⇔ linear



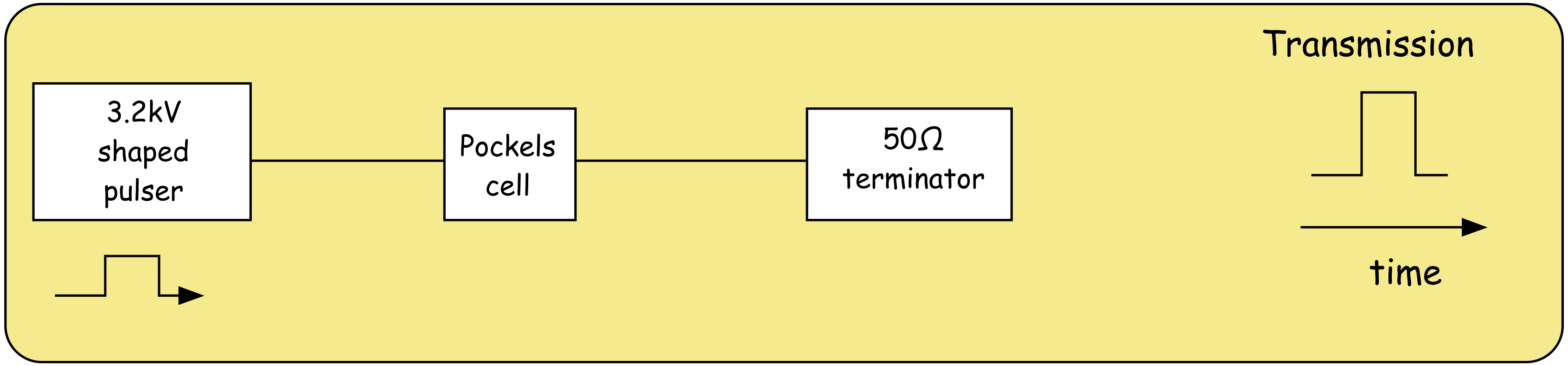
In the crystal the light has equal components parallel to and perpendicular to the C axis.

On application of an electric field along the direction of propagation one of these waves sees a longer optical path by $\lambda/2$

At the exit from the crystal the two waves recombine to form a wave with polarisation orthogonal to the input.

The electric field can be applied in around 50ps in small devices.

Driving a Pockels Cells



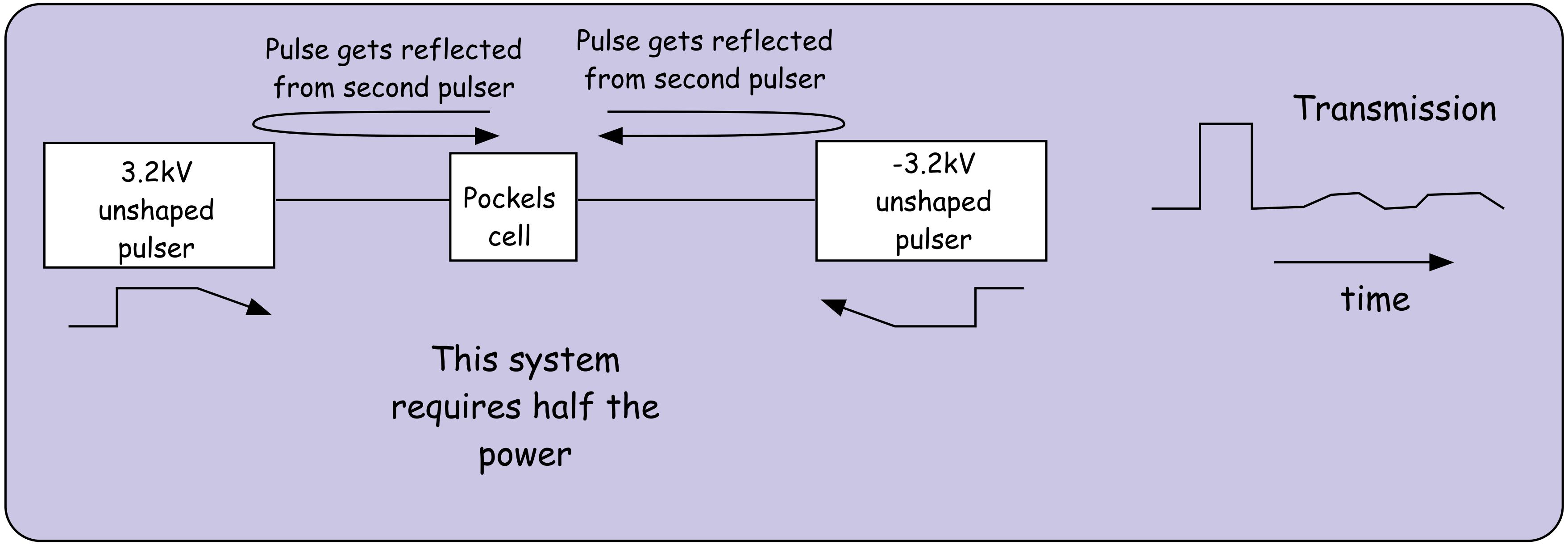
3.2kV shaped pulser

Pockels cell

50Ω terminator

Transmission

time



Pulse gets reflected from second pulser

Pulse gets reflected from second pulser

3.2kV unshaped pulser

Pockels cell

-3.2kV unshaped pulser

Transmission

time

This system requires half the power