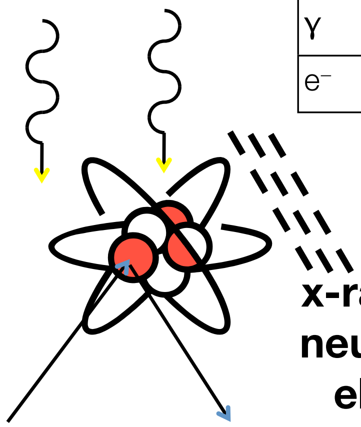
X-ray Detection

	Brightness	Mean Free Path	Absorption Length	Spatial Resolution
	/cm^2/sr/eV	nm	nm	nm
n	10^{14}	10^{7}	10^{8}	10^{6}
γ	10^{26}	10^{3}	10^{5}	10^{1}
e$^-$	10^{29}	10^{1}	10^{3}	0.05



x-ray scattering (probe electronic states)
neutron scattering (probe nuclear states)
electron microscopy (focus, Coulomb interactions)

Peter Denes
Lawrence Berkeley National Laboratory

Outline

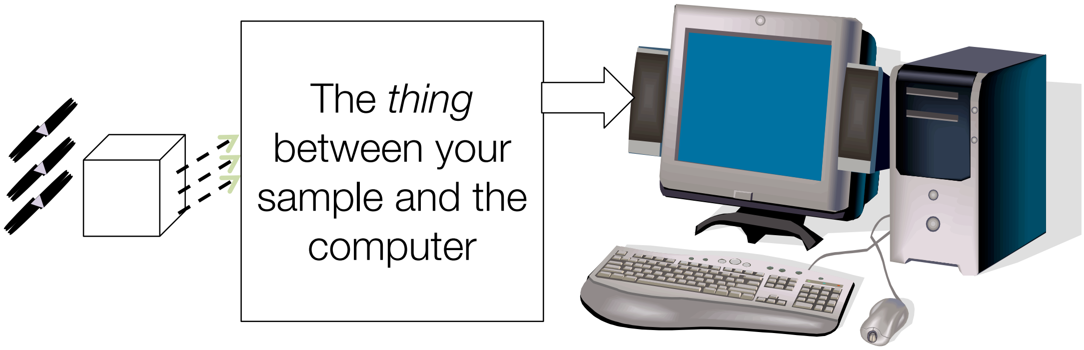
- Basic concepts
  - "phenomenological"
    - Field of "detectors" is a bit more than 100 years old.
      - Can't cover everything
      - Lots of terminology, much of it outdated
  - what can be measured
    - or so you think!
- Types of detectors
  - With emphasis on semiconductor detectors
- Silicon imaging detectors (what I do)

Legend

Concept	Detector concepts 1D, 2D; Direct, Indirect; Counting, Integrating; spatial and temporal performance
Detection	Detection concepts Physics of the detector
Electronics	Electronics
Detector	All of the above
Data	Data

Concept

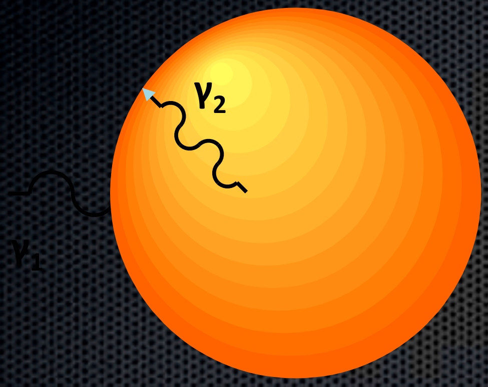
“Detector”



The *thing* between your sample and the computer

Distinguish between detector systems that fit the picture above (i.e. they have an ~ immediate electronic output) and those that are indirect (or use human processing)

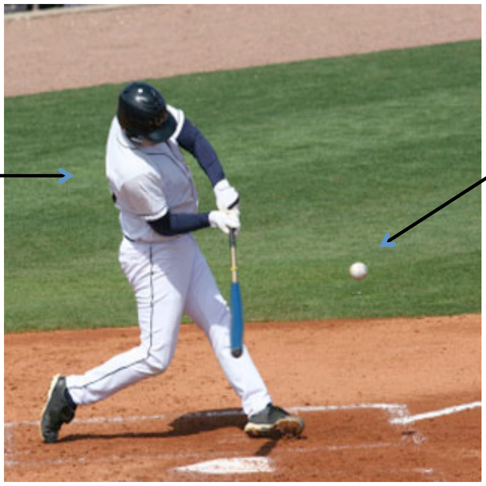
Ideal Detector



- Spatial information
  - $(x, y)_{\gamma 2}$
- Temporal information
  - $t(\gamma_2)$
- Energy information
  - $E_{\gamma 2}$
- With
  - High efficiency
    - $P_{DETECT}(\gamma_2) = 1$
  - 4π solid angle
  - low cost

Spatial Detectors

- “Count ‘hits’”
- Spatial (or temporal) distribution
- “0”, “1”, “2” dimensional detectors



Detection system

Particle to be detected

Quantum Efficiency

Baseball:
Batting Average = hits / at bats

Particle detection:
Quantum efficiency= detected / incident quanta

Note that the Q.E. may depend on the energy of the incident quanta (we'll come back to this)

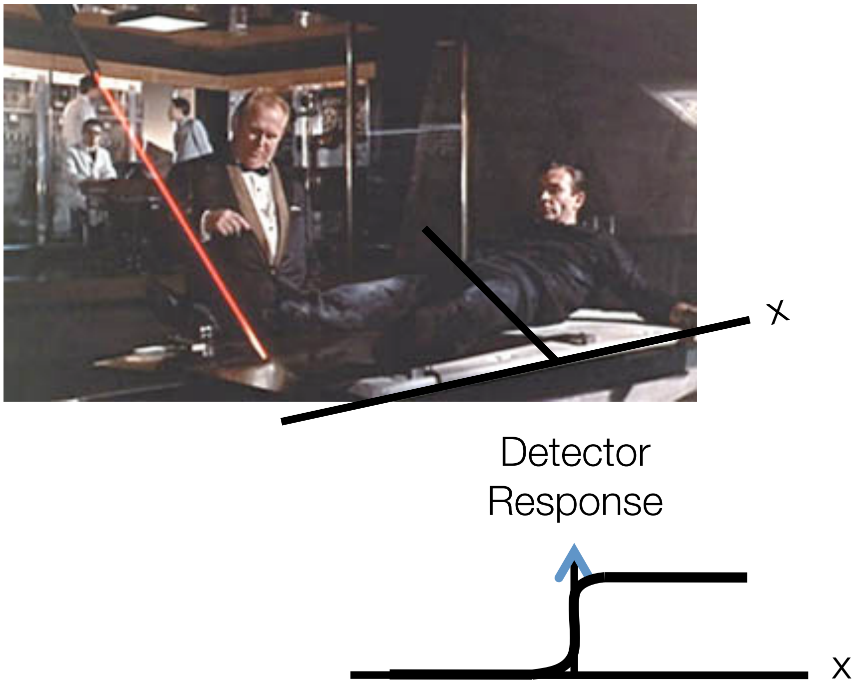
Timing and Energy Resolution

- Our example has timing resolution
  - σ(t) is pretty good
  - ε(t) may not be that good
- Our example also has energy resolution
  - σ(E) more complicated

Calorimetric Photon Detector

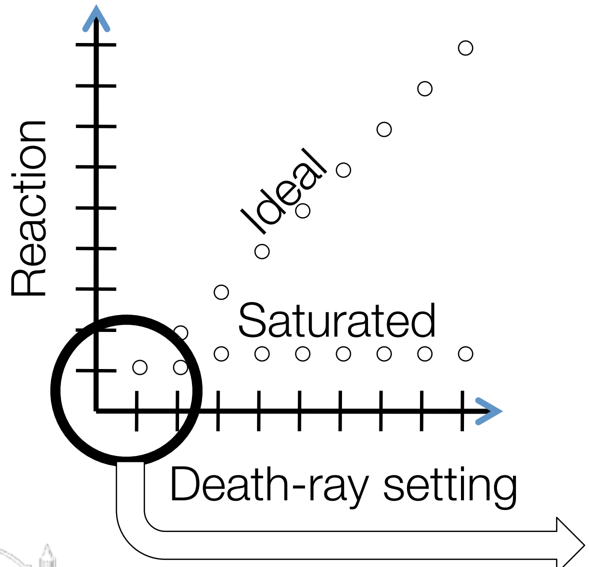
Calorimetric detector: absorbed energy measured by change of temperature
(more generally, “calorimeters” measure total absorbed energy)
[superconducting calorimetric detectors]

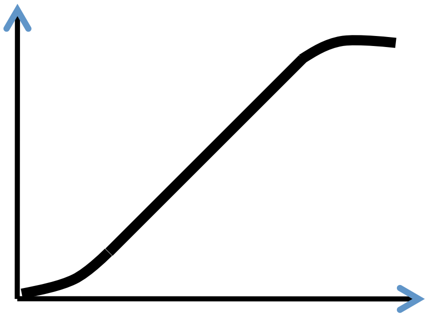
Detector Behavior



Detector Linearity

e.g. diffraction





Spatial Detector Properties

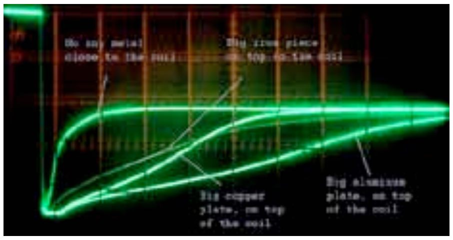
A "point" detector ("0D")
Responds to hits in sensitive area

No way to know where in the sensitive area the hit occurred

There may be additional information

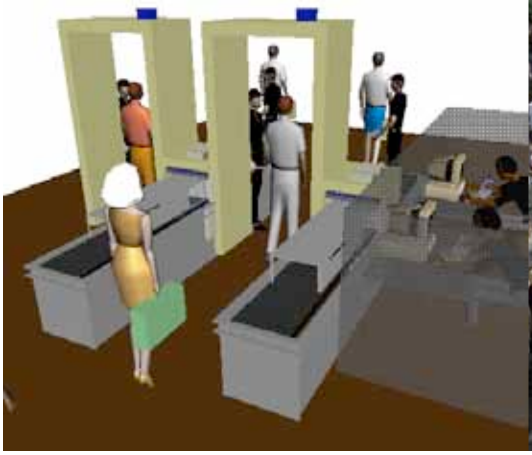
Day-to-day 0D Detector Example

Airport (pulsed induction)
metal detector



"yes / no" – along with
additional information

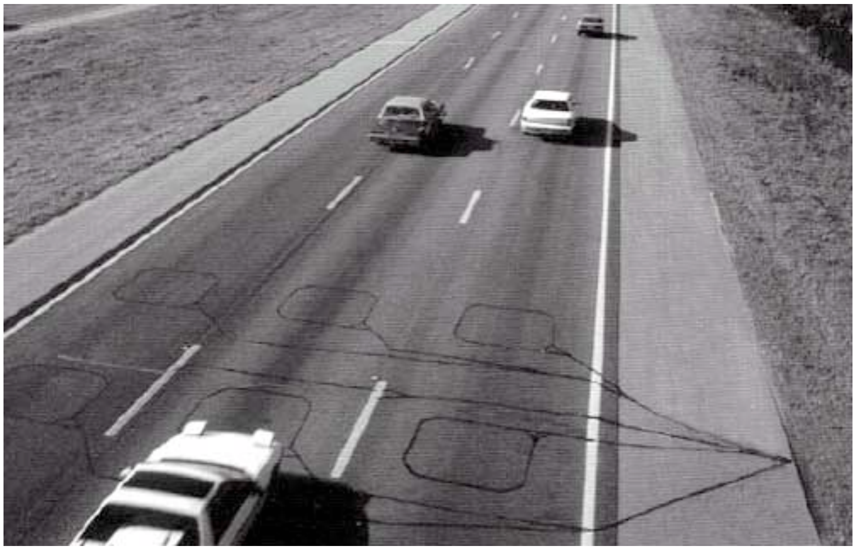
Day-to-day 1D Example



Theory

Experiment

Day-to-day 2D Detector Example



$v=\Delta x/\Delta t$

An Example 2D Detector

- 2D arrangement of our 0D detector elements
- Which are quite non-linear
- Arranged in random sizes and orientations
- But with each element very small

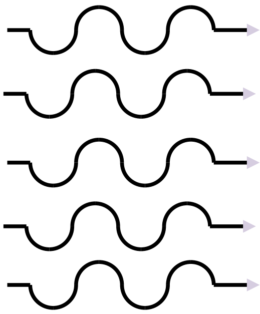
Early X-ray Detection

Herr Röntgen

Frau Röntgen

Schematic of Experiment

Incident Radiation

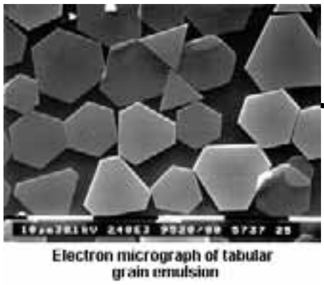


Variable Density Attenuator

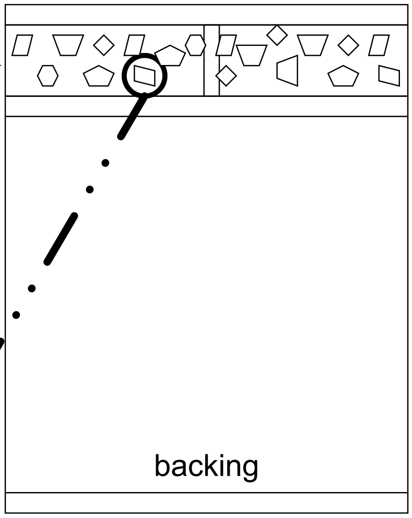
Detector

Image

The Detector – Photographic Film*


Electron micrograph of tabular grain emulsion

AgX + gelatin
(emulsion)



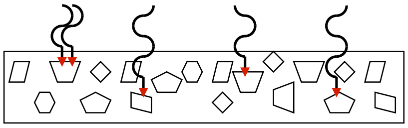

Silver halide emulsion on tri-acetate backing

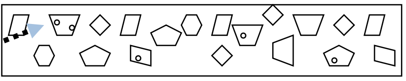
sub-micron to few micron grains

*Primitive, but still unbeaten for certain things

How it Works

Incident light

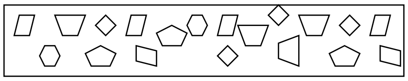




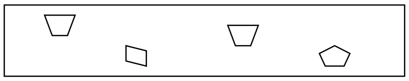
phototelectrons convert Ag^+ sites to Ag^0 – at the same time, thermal fluctuations tend to “erase” the image. Generally, a few (visible) photons are required to leave a “latent” image on a grain

larger grains have larger cross section, so they are more likely to get hit. Thus, larger grains are “faster” but “grainier”

How it Works



"develop" the image so that the sensitized AgX is reduced to black metallic silver



"fix" the image – removing the unexposed AgX

The chemistry and physics of photographic film is not trivial

---

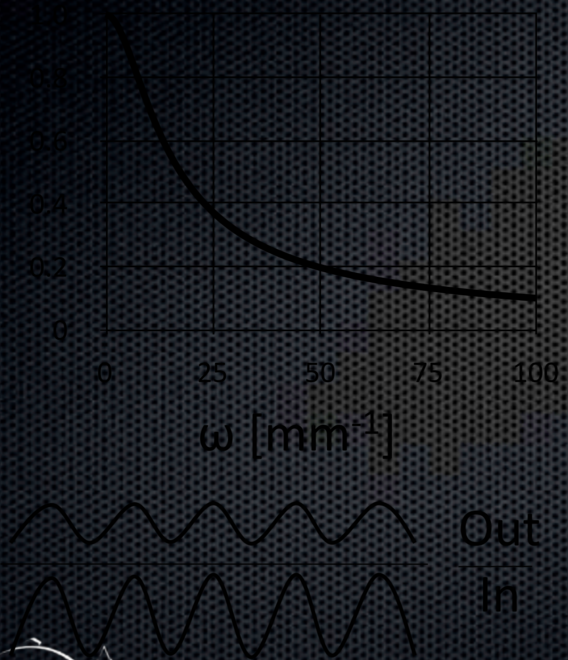
Spatial Imaging Characteristics – PSF

- Point Spread Function
  - δ-function input
  - PSF(x_0, y_0, x, y)
- Image is convolution of input at PSF
- "Black box" PSF includes all effects that might broaden or scatter the input

Spatial Imaging Characteristics – MTF

- Modulation Transfer Function
  - sin ωx input
  - MTF(ω)
    - MTF(ω_x, ω_y)
- MTF = | FT(PSF) |
- Related to contrast

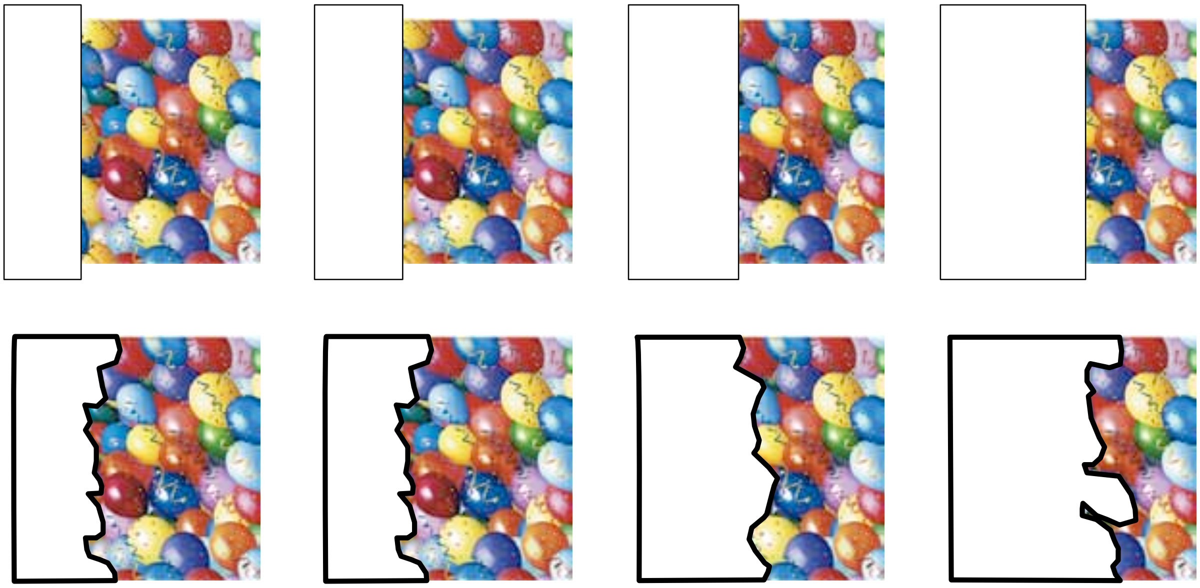
MTF



- Spatial analog to (temporal) frequency response in electronics
  - "Signal processing" also possible
  - e.g. early days of Hubble Space Telescope

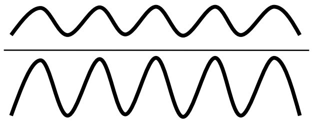
Consider ...

Stepping a knife edge across the film



Spatial Detector Concepts

- Quantum Efficiency
  - Active area
- Contrast (PSF, MTF)
  - Spatial (frequency dependence)



PSF = 0*

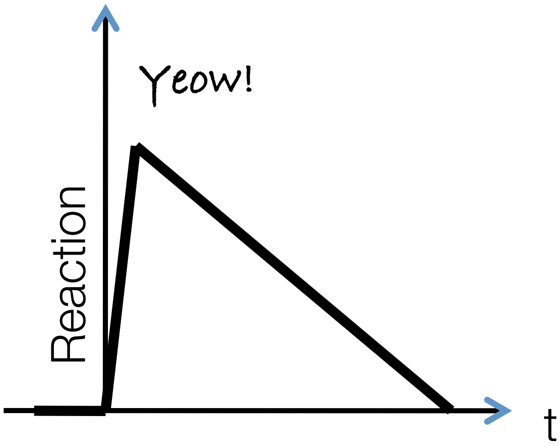
PSF = 1%

PSF = 5%

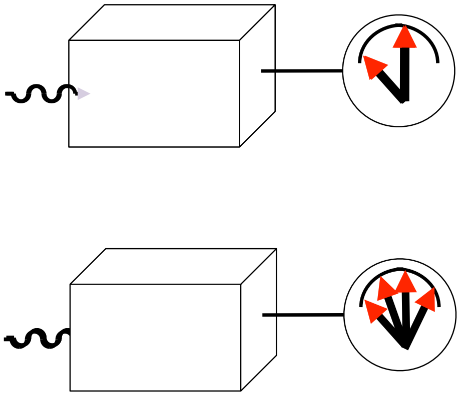
*of full image dimension

Detector Temporal Response

Pulsed Operation



“Counting” and “Integrating”



Consider temporal characteristics of

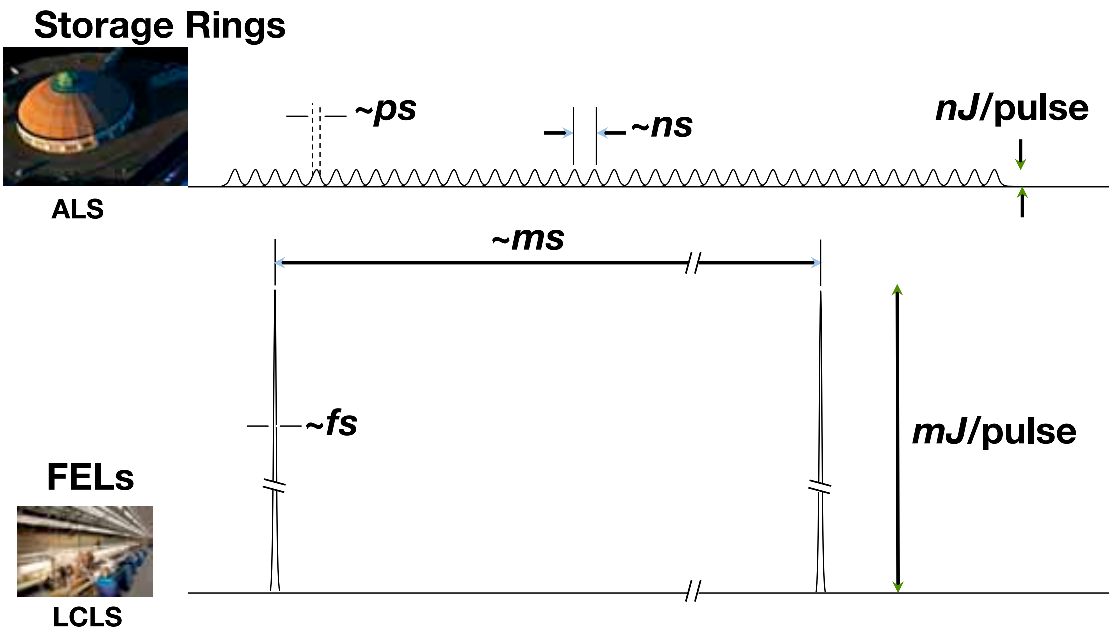
- source
- detector

“Counting” and “Integrating”

- $\Delta t\,(\gamma_1, \gamma_2) >> \tau_{DETECTOR}$, and $P(N_\gamma > 1) << 1$
  - Detector “counts” single photons
- $\Delta t\,(\gamma_1, \gamma_2) >> \tau_{DETECTOR}$, and $P(N_\gamma > 1) \cancel{<<} 1$ **and** detector can quantize N_γ
  - Detector “counts” single photons
- $\Delta t\,(\gamma_1, \gamma_2) \cancel{>>} \tau_{DETECTOR}$
  - Measure a “current” $<I>=<dq/dt>$

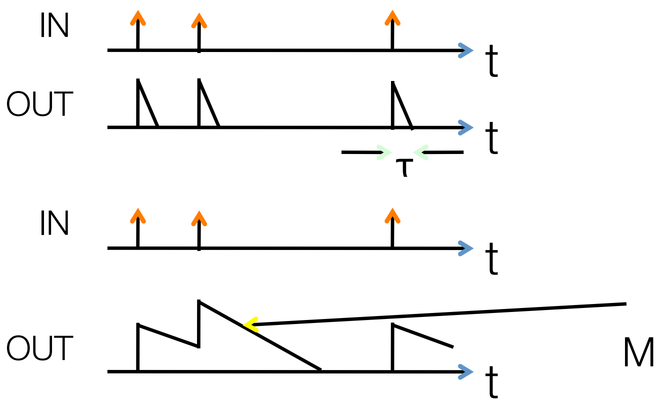
- Example: ALS Δt_{BUNCH} = 2 ns, LCLS Δt_{BUNCH} = 8 ms →

Storage Rings and FELs



FEL detector can not count individual photons (they all arrive at the same time)

Pileup, Double Pulse Resolution



Pileup
May or may not be a problem
(can recover with signal
processing)

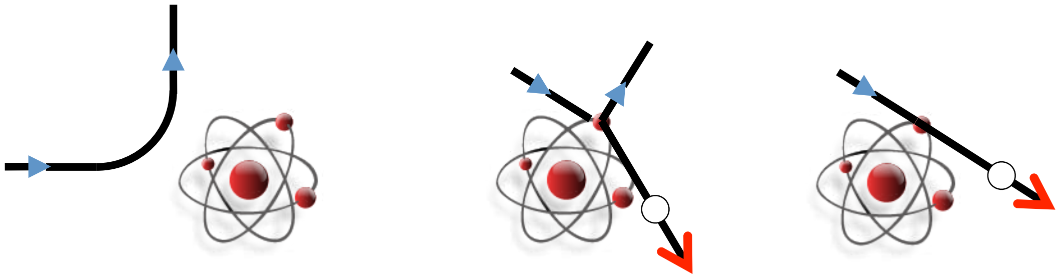
If photons arrive synchronously, maximum rate ~ 1/τ
If photons arrive at random, maximum rate ~ 1/10τ

Look Further Into "Detector"

- *Rarely* does a (practical) photon detector actually detect photons
- Generally the photon is converted into one (or more) secondary particles
- Those secondary particles (usually electrons) are then detected, or create tertiary particles which are detected
- $\gamma \rightarrow e^-$

X-ray Interaction in *Detector*

Practically speaking, 3 possibilities:



Elastic
Scattering

Compton
Scattering

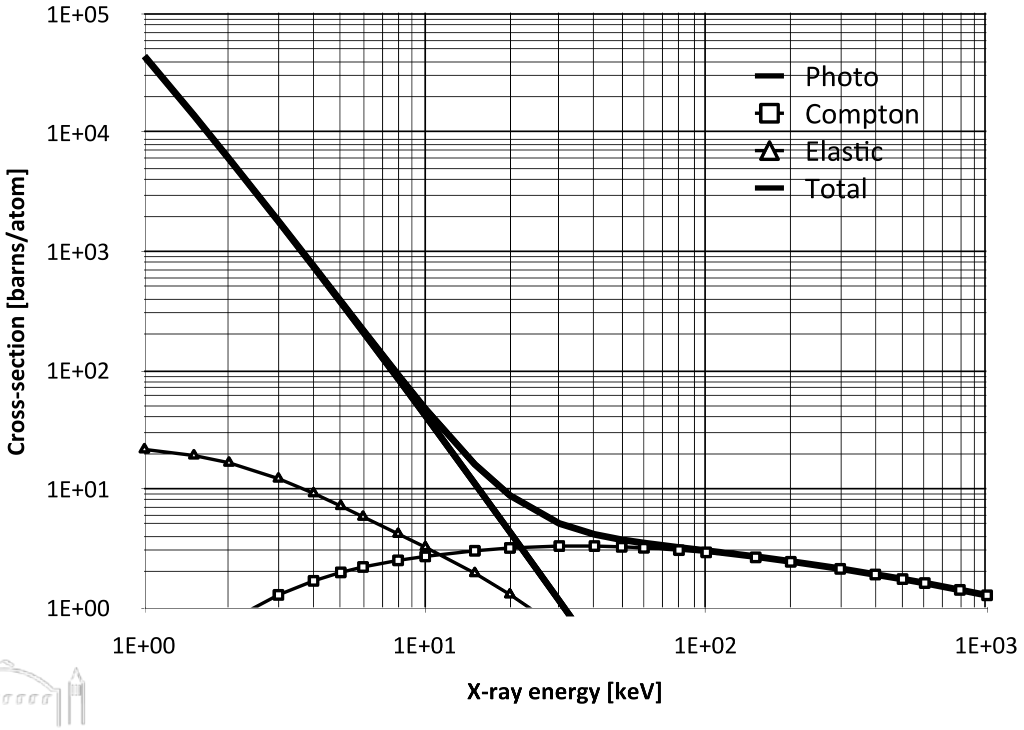
Photoelectric
Absorption

$E_e \neq E_\gamma$

$E_e = E_\gamma$

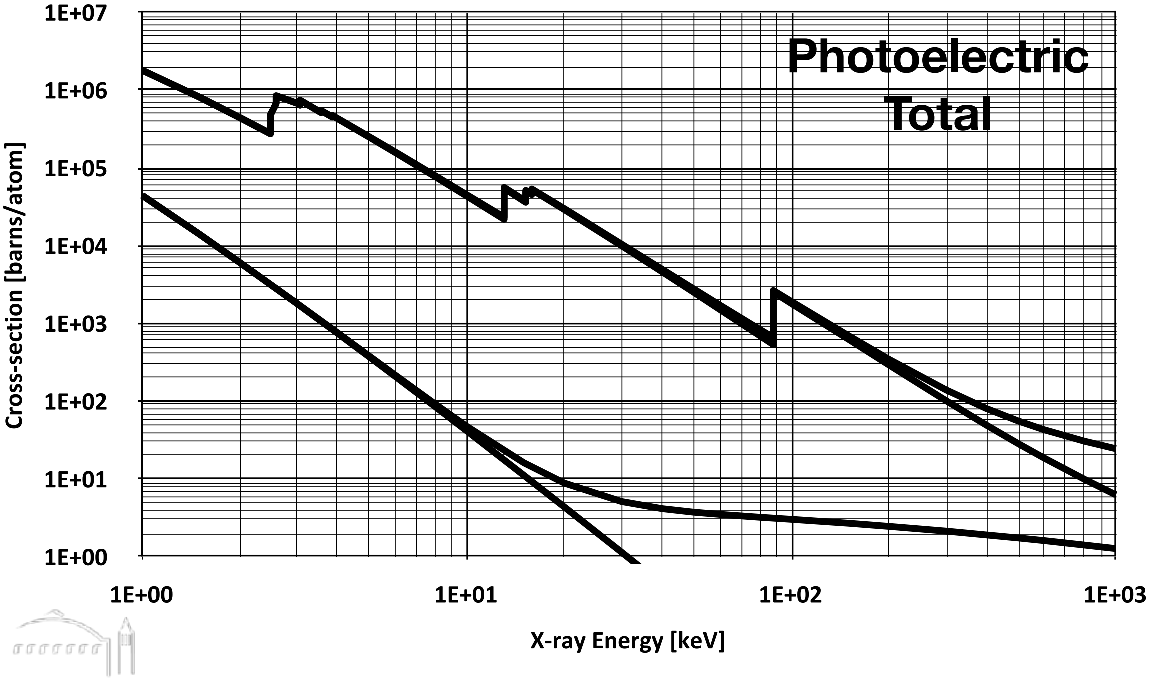
Electron range (very crudely) R [μm] ≈ E [keV]

X-ray cross-section in Carbon



X-ray cross-sections in Carbon and Lead

For detector, high σ and all photoelectric



Effect of Z (Detector) and E

The only thing photons are good for is to make electrons

Photoelectric Absorption:

$\sigma \sim Z^n/E^3$

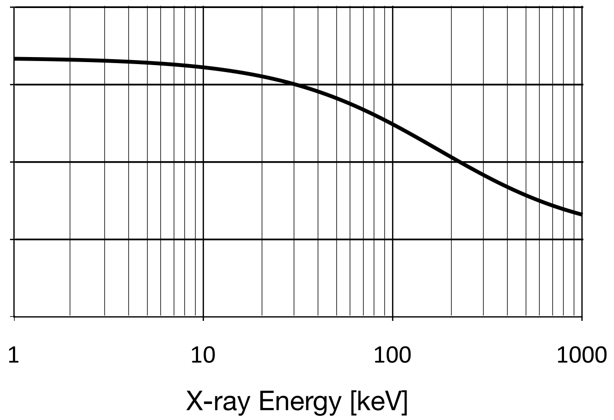
$n \sim 4 - 5$

$Z\uparrow \Rightarrow \sigma\uparrow$

Scattering

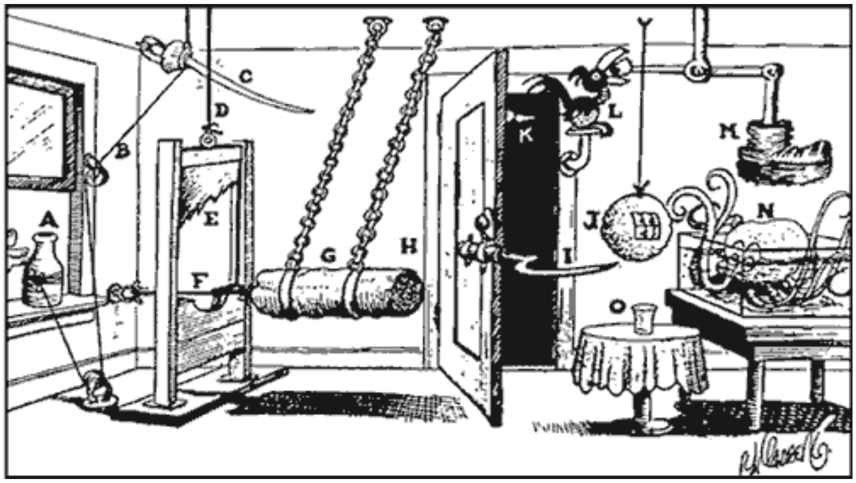
$\sigma \sim Z\,x$

(curve)



Scattering is elastic (e⁻ stays in ground state) or Compton (e⁻ ejected)

Quantum Efficiency (again)



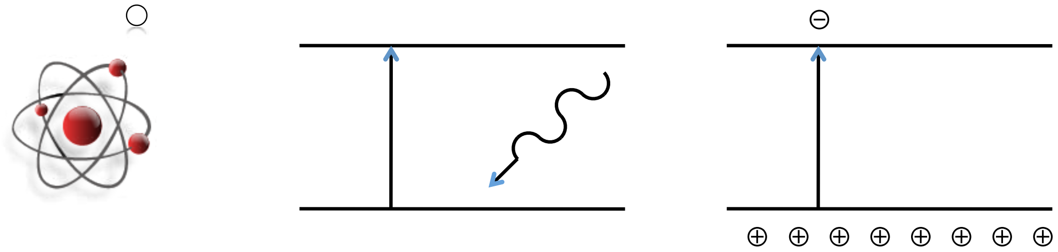
- Probability of detecting incident photon
  - Photon has to create ionization electron
  - Ionization electron has to be detected

What can the Ionization Electron Do?

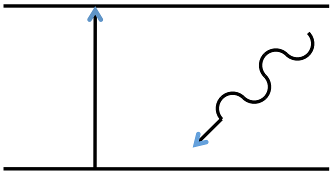
Form free charge

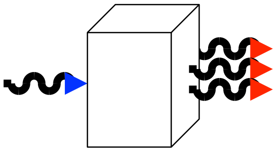
Scintillation (radiative)

Charge collection in semiconductor



Scintillator

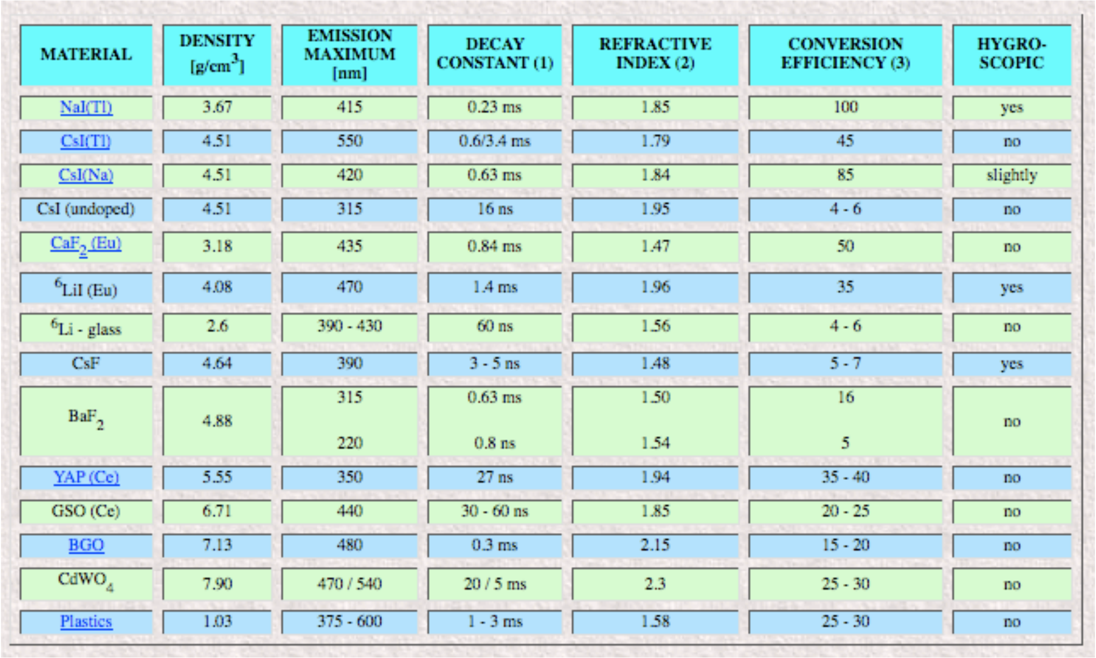




“Converts” x-ray (or other higher energy particle) into visible light

- Organic
- In-organic
- Mono-crystals
- Powders
- Liquids
- Plastics
- …

ρ, τ, N_γ, …

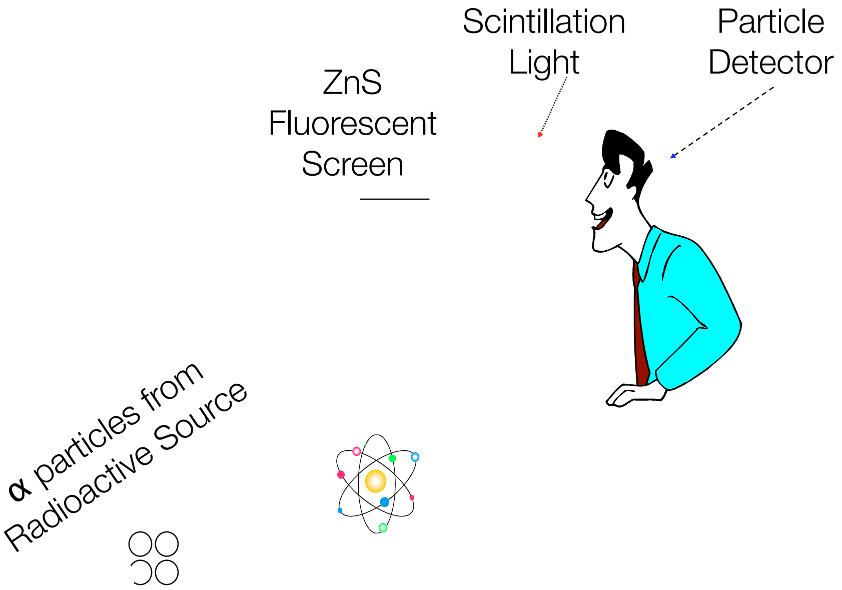


MATERIAL	DENSITY [g/cm^3]	EMISSION MAXIMUM [nm]	DECAY CONSTANT (1)	REFRACTIVE INDEX (2)	CONVERSION EFFICIENCY (3)	HYGRO-SCOPIC
NaI(Tl)	3.67	415	0.23 ms	1.85	100	yes
CsI(Tl)	4.51	550	0.6/3.4 ms	1.79	45	no
CsI(Na)	4.51	420	0.63 ms	1.84	85	slightly
CsI (undoped)	4.51	315	16 ns	1.95	4 - 6	no
CaF_2 (Eu)	3.18	435	0.84 ms	1.47	50	no
^{6}LiI (Eu)	4.08	470	1.4 ms	1.96	35	yes
^{6}Li - glass	2.6	390 - 430	60 ns	1.56	4 - 6	no
CsF	4.64	390	3 - 5 ns	1.48	5 - 7	yes
BaF_2	4.88	315 220	0.63 ms 0.8 ns	1.50 1.54	16 5	no
YAP (Ce)	5.55	350	27 ns	1.94	35 - 40	no
GSO (Ce)	6.71	440	30 - 60 ns	1.85	20 - 25	no
BGO	7.13	480	0.3 ms	2.15	15 - 20	no
$CdWO_4$	7.90	470 / 540	20 / 5 ms	2.3	25 - 30	no
Plastics	1.03	375 - 600	1 - 3 ms	1.58	25 - 30	no

For more, see http://scintillator.lbl.gov/

Visible Scintillation Counting

e.g. Rutherford 1911 - Discovery of the nucleus



Scintillation Light

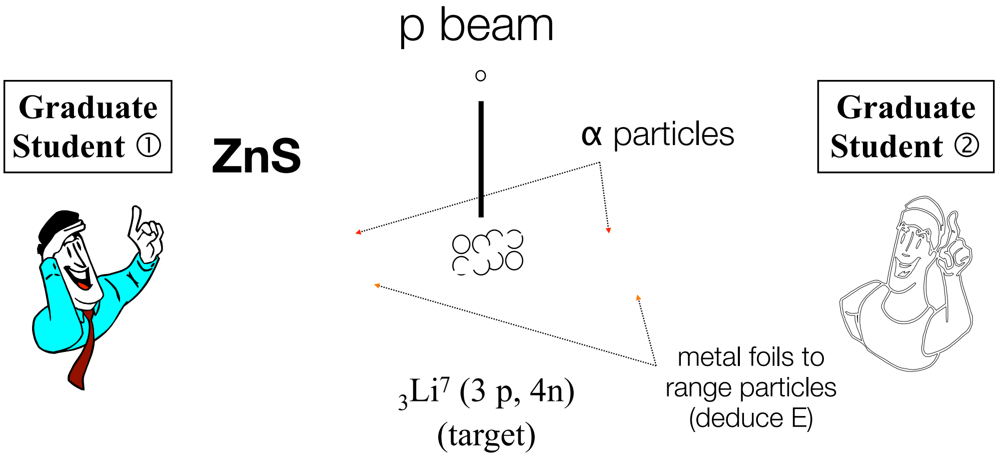
Particle Detector

ZnS Fluorescent Screen

α particles from Radioactive Source

Coincidence Experiment

Cockcroft+Walton, 1932



p beam

Graduate Student ①

ZnS

α particles

Graduate Student ②

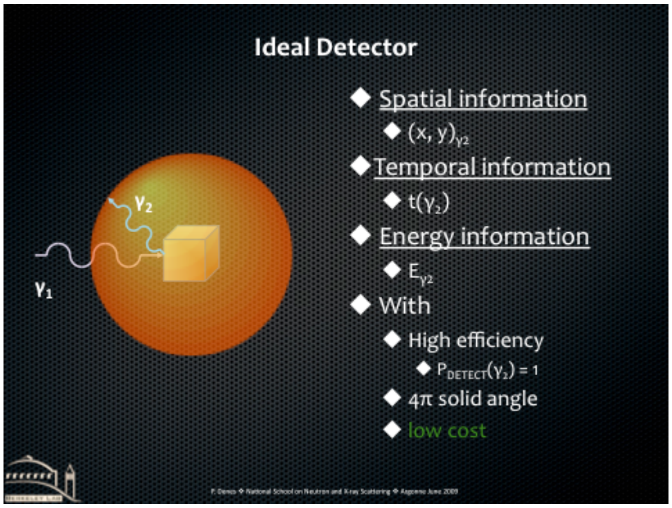
metal foils to range particles (deduce E)

$_3Li^7$ (3 p, 4n)
(target)

First demonstration that E (from $p + {}_3Li^7 \rightarrow \alpha + \alpha$) = Δmc^2

(Δm is difference between initial and final nuclei masses)

Detector Properties



Ideal Detector

- <u>Spatial information</u>
  - $(x, y)_{\gamma 2}$
- <u>Temporal information</u>
  - $t(\gamma_2)$
- <u>Energy information</u>
  - $E_{\gamma 2}$
- With
  - High efficiency
    - $P_{DETECT}(\gamma_2) = 1$
  - 4π solid angle
  - low cost

P. Denes ❖ National School on Neutron and X-ray Scattering ❖ Argonne June 2009

2 x 0D detectors

Coincidence technique
~Hz data rate

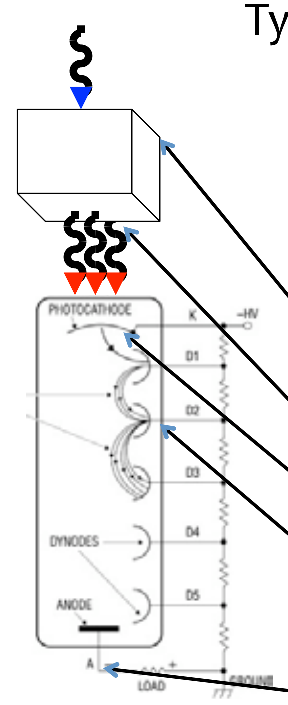
E via attenuation

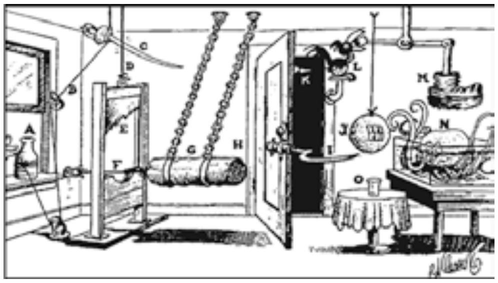
Advantages and Disadvantages

- Low Power (graduate students don't need much food)
- Low Speed - counting rate limitations ~ 1 Hz
- Threshold sensitivity
  - (although Marsden could distinguish α and p by brightness)
    At λ ~ 500 nm, $\text{Threshold}_{\text{TRAINED OBSERVERS}}$ ~ 17 γ for tFLASH > 40 µs
- Yield: "*...at one famous laboratory during this period all intending research students were tested in the dark room for their ability to count scintillations accurately. Only those whose eyesight measured up to the standards required were accepted for nuclear research; the others were advised to take up alternative, less exacting, fields of study*"

From Birks

Typical Scintillation Detector





- Incident photon creates (ionizing) photo-electron
- Ionization generates visible photons
- Visible photons converted into electrons
- Electrons “amplified” by secondary emission
- Output current detected

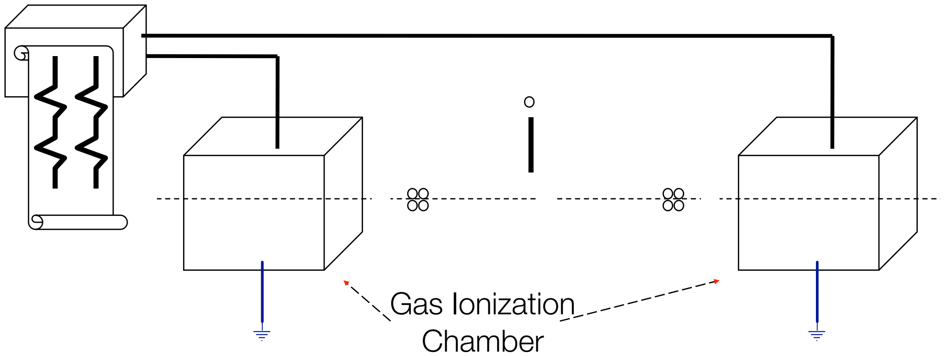
Photomultiplier

Coincidence Experiment

Cockcroft+Walton - Electronic Verification

One of the last visual counting experiments
(and one of the first electronic counting experiments)

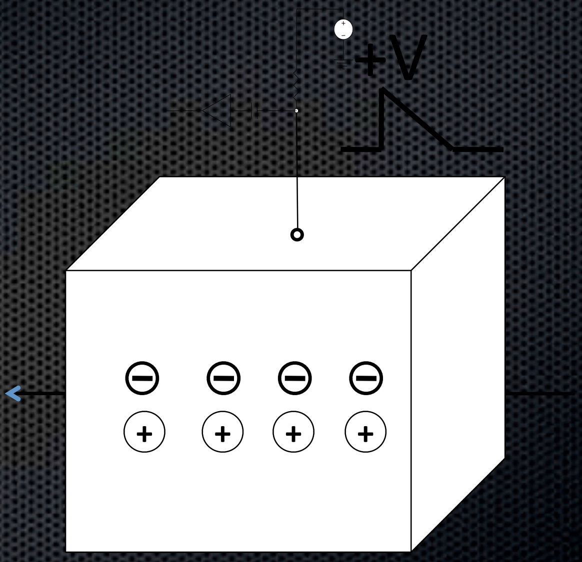
Oscillograph



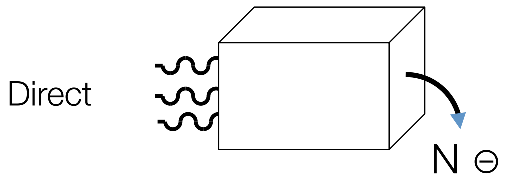
Gas Ionization
Chamber

Ionization Chamber

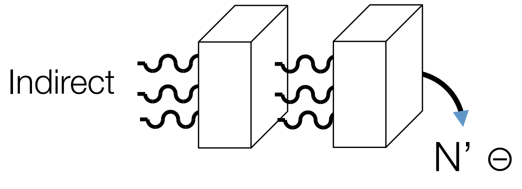
- Particle passes through chamber and creates an ionization track
  - Image charge Q_0 appears on positively charged plate
- Electrons move (with speed = ***drift velocity***) towards positively charged plate
  - As the electrons arrive, they reduce the charge on the plate
- A current pulse has been created at the same time the particle has passed through the chamber



Electronic Detectors



Incident radiation converted into N charges inside “Sensor”



Incident radiation converted into some other form of radiation, which in turn is converted into N’ charges inside “Sensor”

Historical terms
Semi-meaningless

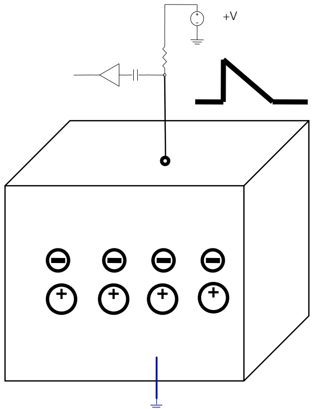
Energy Needed for Detection

“Sensor”	η = E per secondary quanta	Mechanism
Gas	30 eV	e⁻/ion pairs
Scintillator	10 – 1000 eV	optical excitation
Semiconductor	1 – 5 eV	e⁻/hole pairs
Superconductor	~meV	breakup of Cooper pairs
Superconducting calorimeters	~meV	phonons

Stolen from H. Spieler

Statistics – Fano Factor

“Sensor”	η = E per secondary quanta	Mechanism
Gas	30 eV	e⁻/ion pairs
Scintillator	10 – 1000 eV	optical excitation
Semiconductor	1 – 5 eV	e⁻/hole pairs
Superconductor	~meV	breakup of Cooper pairs
Superconducting calorimeters	~meV	phonons



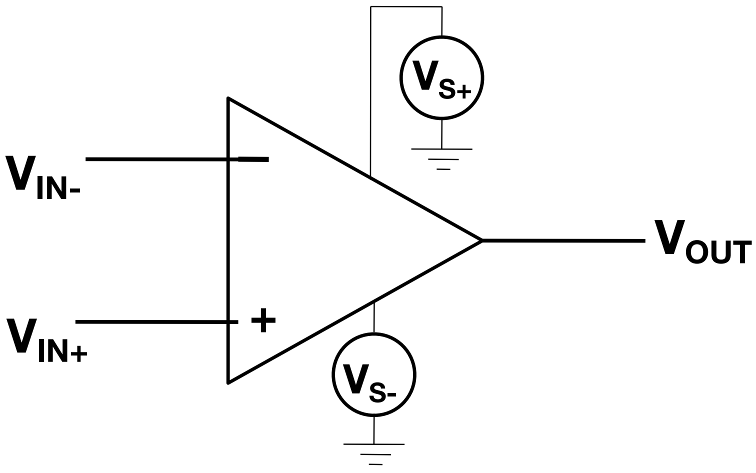
$$N_{\pm} = \frac{E}{\eta}$$

$$\sigma_N = \sqrt{FN}$$

- *Intrinsic* resolution is *Fano-limited*
- σ_N/N ↓ as η ↓
  - Hence interest in superconducting calorimeters
- There are additional ways to have fluctuations on N

Next Problem – the current pulse is usually very small

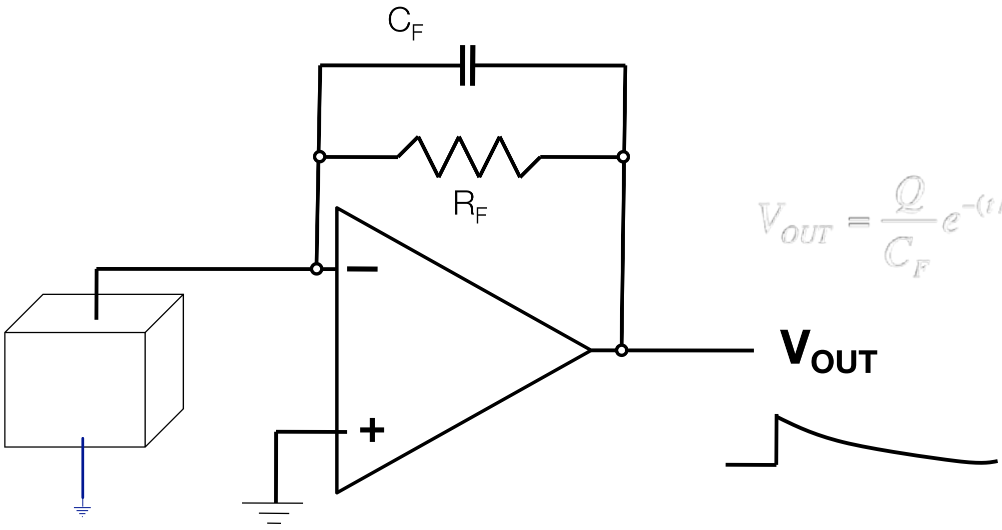
It must be amplified



$$V_{OUT} = \begin{cases} V_{S+} \text{ if } V_{IN+} > V_{IN-} \\ V_{S-} \text{ if } V_{IN+} < V_{IN-} \end{cases}$$

Let's take this further (70 years of electronics in 3 seconds)

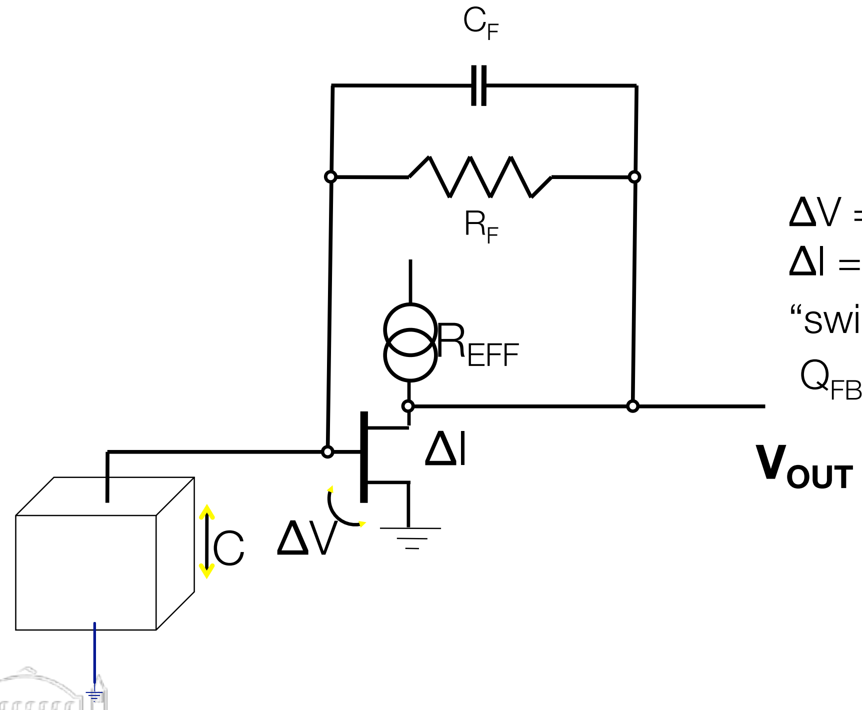
Charge-sensitive pre-amplifier



$$V_{OUT} = \frac{Q}{C_F} e^{-(t/R_F C_F)}$$

Charge appears all at once (δ function)

Almost Always Like This



$\Delta V = Q/C$

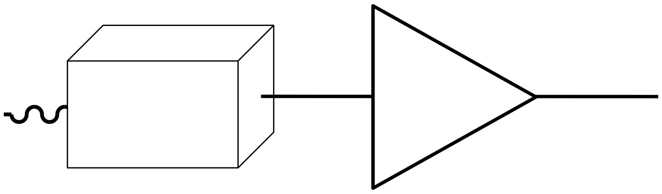
$\Delta I = g_m \bullet \Delta V$

"swing" = $\Delta I \bullet R_{EFF}$

$Q_{FB} = Q = C_F \bullet V_{OUT}$

Noise and Statistics

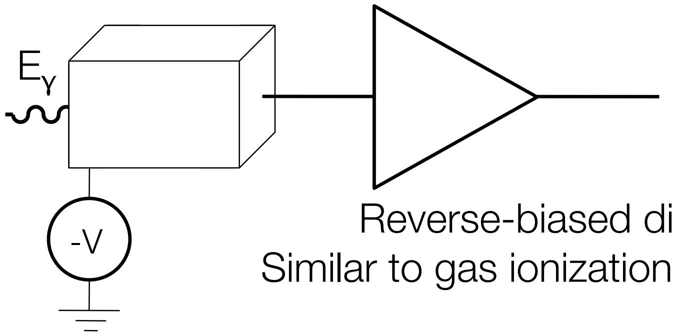
Some terms to get started



- Incident photon creates electron of energy E_γ (photoelectric) or < E_γ (Compton) (with probability "QE")
- Electron creates **on average** $N = E_e/\eta$ e/h pairs
- Output pulse height = Gain x N Volts
- Output electronic noise V_N Volts

Semiconductor Detector

p-i-n diode



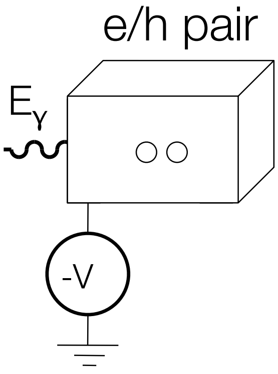
Reverse-biased diode
Similar to gas ionization chamber

$$N = E_\gamma/\varepsilon$$

$$\sigma^2_N = F \bullet E_\gamma/\varepsilon$$, F = Fano factor

Material	Si	Ge	GaAs	Diamond
η [eV]	3.6	3.0	4.4	13.1
F	0.12	0.13	0.10	0.08
ρ [g/cm^3]	2.3	5.3	5.3	3.5

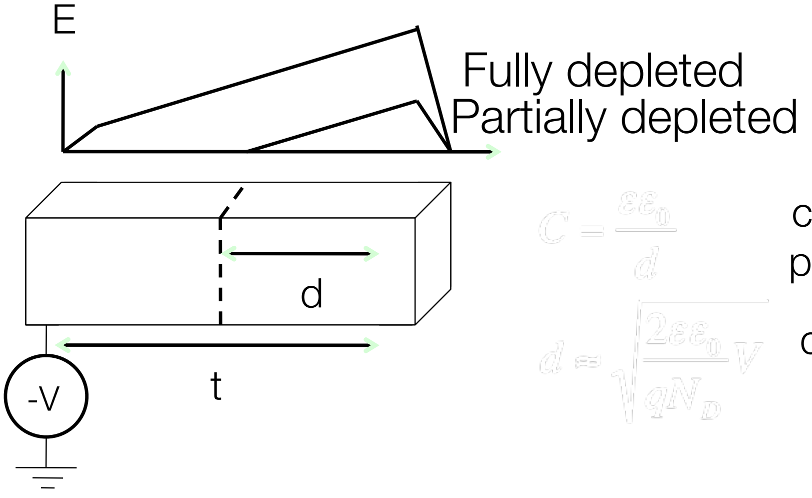
How it Works



- Recombination
  - e^- recombination time $\propto 1/$ hole concentration
- Diffusion
  - In field-free region, e^- diffuses (into 4π)
    $D = (kT/q)\mu$ (μ = mobility)
- Drift
  - In non-zero field region e^- moves towards postive plate with velocity $\mu \bullet E$

Depletion

Fully depleted → minimize diffusion (and recombination)

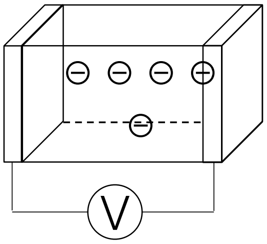


$$C = \frac{\varepsilon\varepsilon_0}{d}$$ capacitance per unit area

$$d \approx \sqrt{\frac{2\varepsilon\varepsilon_0}{qN_D}V}$$ depletion depth

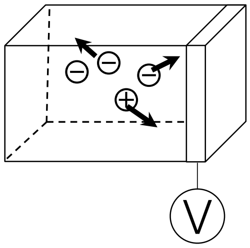
---

Importance of Depletion



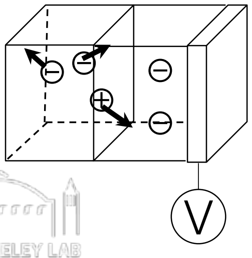
◆ **Fully depleted detector**

No recombination – collect all charge (spectroscopic)
Charge drifts to collection electrode
PSF = 0 (best spatial resolution)



◆ **Undepleted detector**

Diffusion + recombination
Poorer PSF
Poorer spectroscopic capability



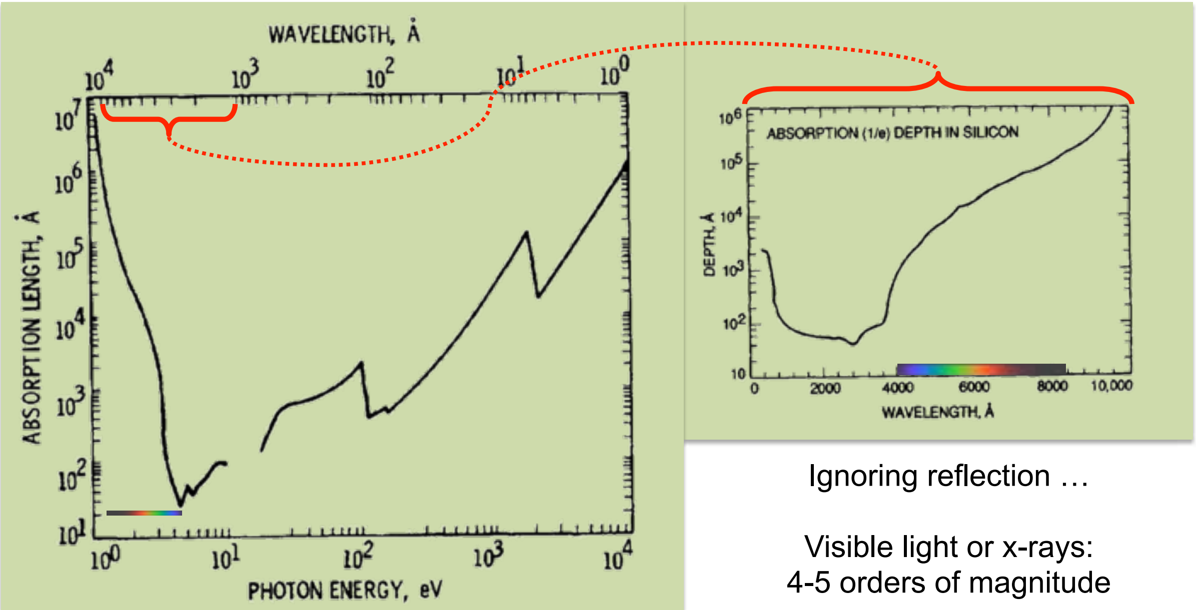
◆ **Partially depleted detector**

PSF and charge collection depend on site of photoconversion

Charge collection

- drift - all charge drifts directly towards anode
- diffusion - charge goes into 4π
- recombination - no charge collected

Absorption in Si



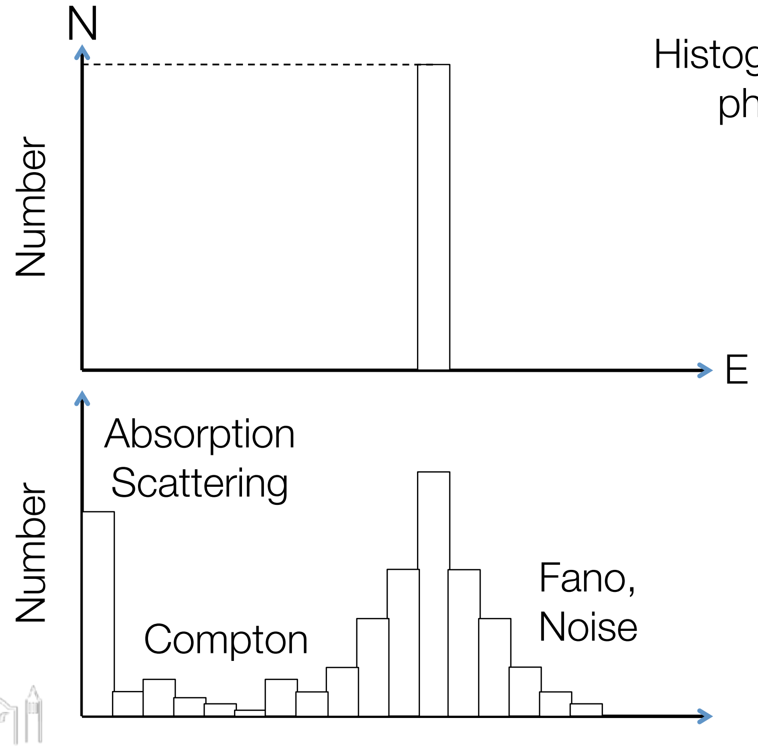
Ignoring reflection …

Visible light or x-rays:
4-5 orders of magnitude

Bandgap of Si at 300K = 1.1 eV
pure Si transparent for λ > 1.1 μm

From Janesick

Send N X-rays (of Energy E) Into Detector

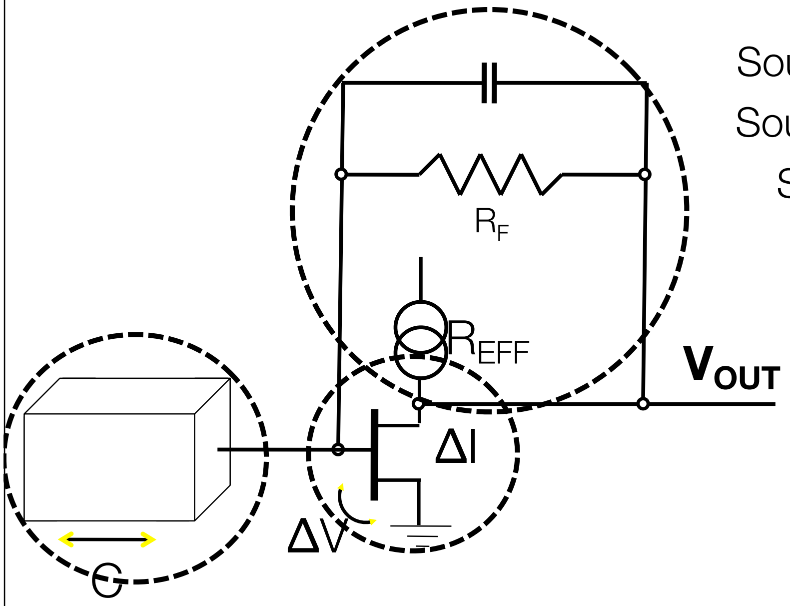


Histograms of detected
photon energies
Σ = N

Desired

Measured

Noise

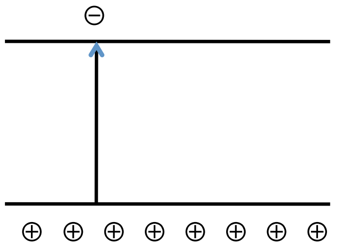


Source #1 – "input stage"

Source #2 – the detector

Source #3 – everything else

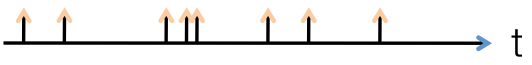
The Detector Makes Noise?



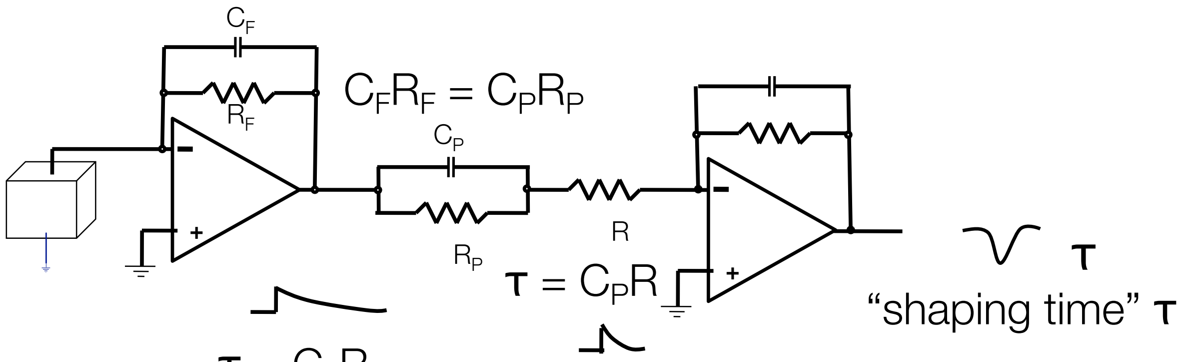
Semiconductor detector i.e. valence band ~full, conduction band ~empty

eV band gaps → **thermal excitation** of carriers

- Thermal excitation
  - "leakage" or "dark" current (I_{LEAK} e^-/s)
  - "looks like" signal
  - ("shot noise")
  - Reduced by cooling
- Noise, $\propto \sqrt{I_{LEAK}}$, because leakage is not orderly



Some More Electronics



$C_FR_F = C_PR_P$

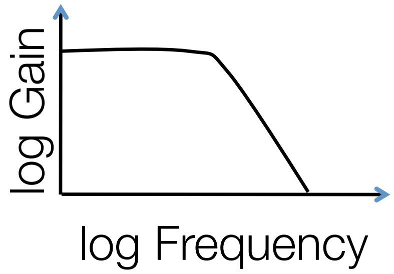
$\tau = C_PR$

"shaping time" τ

$\tau = C_FR_F$

Bandwidth = 1 / 2π τ

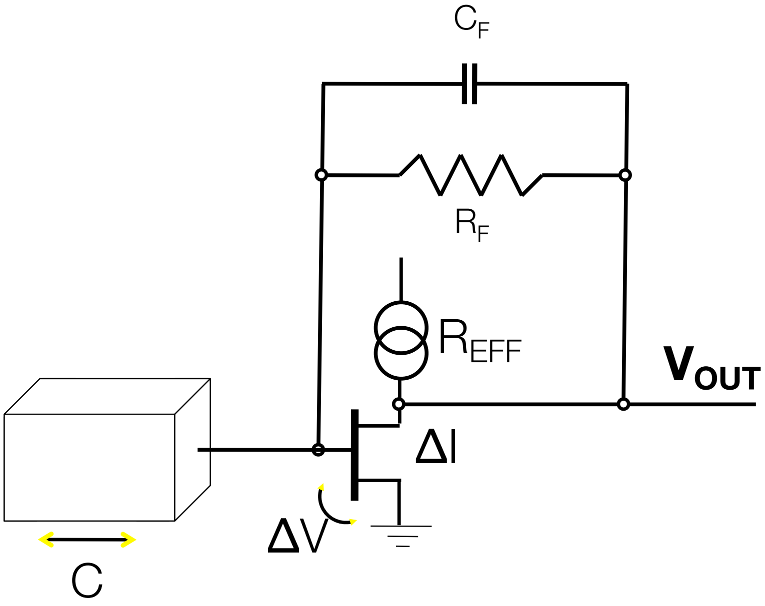
In frequency domain:



Things ∝ τ

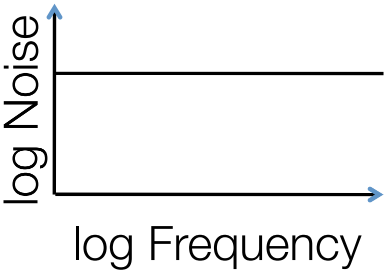
- Double pulse resolution $\Delta t \propto \tau$
- Noise due to leakage current ∝
  - √I – random arrival of leakage charge
  - $I \sim e^{-T}/T^2$
  - √τ – i.e. √[e⁻/s]•[s]
- Longer integration time (τ) increases noise due to leakage current
- Must want **short** integration time

Electronic Noise

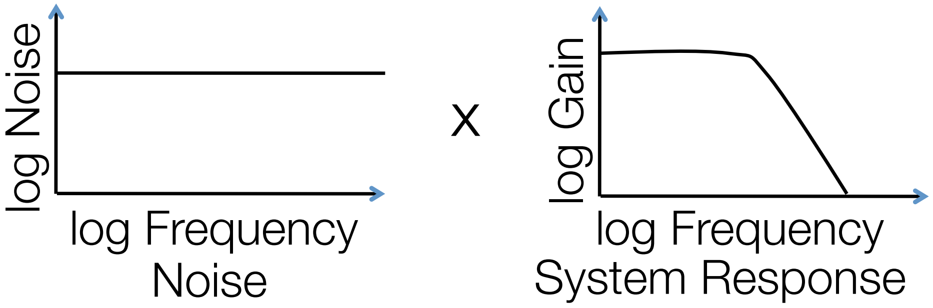


Resistors make noise (Thermal excitation of carriers in resistor means I x R = V_{NOISE}.)

Thermal noise is truly random, $V_N \sim \sqrt{4kTR}$



Contribution of Thermal Noise



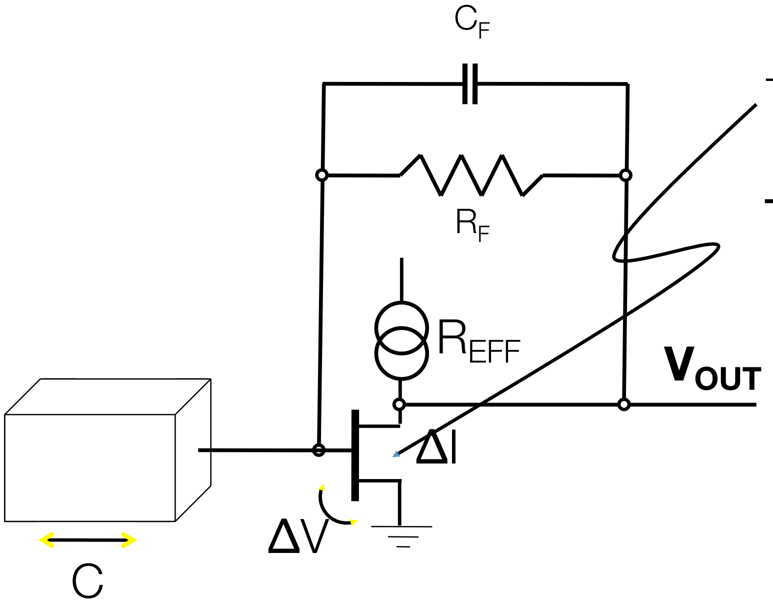
Noise

System Response

- *Noise* is frequency independent
- So response is ∝ √Bandwidth

- Must want **long** integration time

It’s Worse



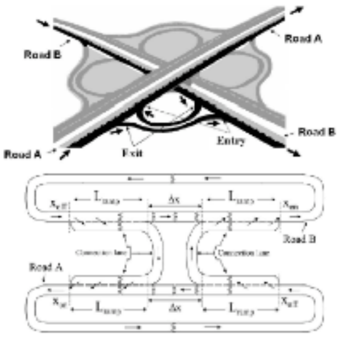
Thermal noise $\sqrt{(4kT/g_m)}$

→ δV_{OUT} (from noise)
Input stage will
“compensate”
Noise “charge” at input
$\delta Q = C_F \delta V_{OUT}$
ΔV (at input) = $\delta Q/C$

Noise ∝ C

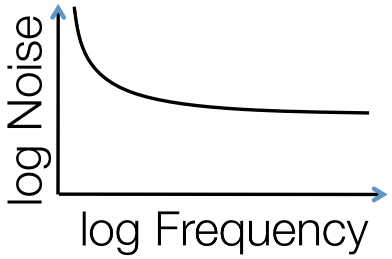
It’s Even Worse

Many physical systems are
subject to fluctuations ~ $1/f^{\alpha}$
You know this from driving:



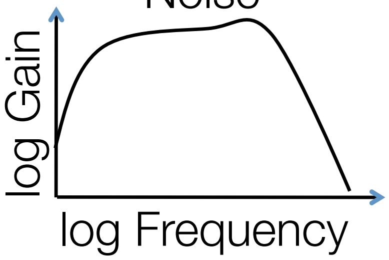
RMS of time you wait getting
onto the freeway ~ 1/f

Same with electronics. So
there is an optimum



Noise

X



System Response

Not so Simple

1. Fluctuations in number of photons "absorbed"
2. Fluctuations in number of secondary particles created
3. (Fluctuations in number of tertiary particles created)
4. Electronic noise

- **Energy** resolution: 2, 3 and 4
- Quantum efficiency: 1 (but maybe 2, 3 and 4)

Detective Quantum Efficiency

- Combine notion of Quantum Efficiency (probability of detecting a particle) with spatial response (probability of detecting/quantifying N(x,y) particles → DQE
  - How faithfully does the detector transfer the (spatially varying) fluctuations of the input signal
  - DQE(ω_x, ω_y)
- Many definitions – most common is $DQE = \frac{(S/N)^2_{OUT}}{(S/N)^2_{IN}}$
- Example, flat field illumination (flux ϕ) of detector with certain QE

$$(S/N)_{IN} = \frac{\phi A\tau}{\sqrt{\phi A\tau}} \quad \text{(Poisson)}$$

$$(S/N)_{OUT} = \frac{QE \times \phi A\tau}{\sqrt{QE \times \phi A\tau + \sigma_N^2}}$$

for electronic noise σ_N

S/N, Dynamic Range, Number of Bits

Usually mis-stated!

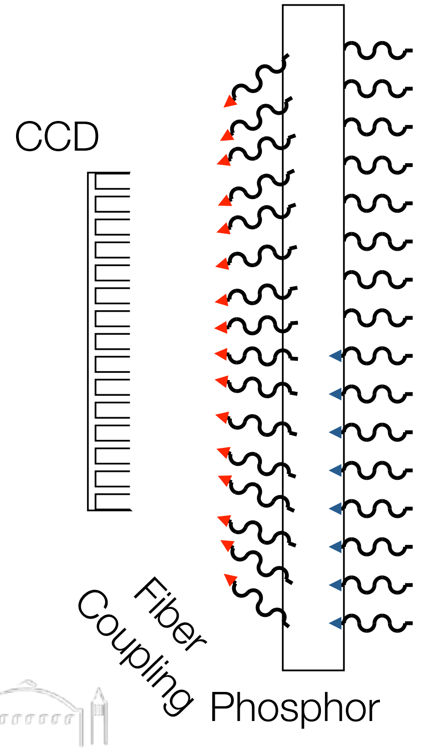
- Si: $\eta = 3.6$ eV. Inject 3.6 keV γs (generates on average 1,000 e/h pairs) and measure the output pulse height → "conversion gain" = Volts / e^- = V_e
- RMS noise at output = V_N
  - **ENC** (*Equivalent Noise Charge*) = V_N/V_e
- If the maximum voltage that the system can measure is V_{MAX}, then the dynamic range is V_{MAX} / V_N
  - Example: $V_e = 1\ \mu V / e^-$, $V_N = 100\ \mu V$
    - ENC = 100 e^- = 360 eV [RMS]
    - $V_{MAX} = 1V \rightarrow DR = 1V / 100\ \mu V = 10^4$
  - $N_{BITS} = ln(DR) / ln(2)$
    - $ln(10^4) / ln(2) = 13$ bits (i.e. $2^{13} \approx 10^4$)
- S/N has specific meanings, that are not any of these!

A tale of 3 different √N

- Uniform flux ϕ [$\gamma/cm^2/s$] on area A yields $N = \phi A$ [γ/s] ± √N incident photons/s
  - photostatistics
- Each one (that is converted) produces $N_\pm = NE/\eta \pm \sqrt{(FN_\pm)}$ e/h pairs/s
  - intrinsic resolution
- Which, as a current sampled in time τ has fluctuations $\sim \sqrt{(N_\pm \tau)}$
  - shot noise

Detector

"Classical" X-ray Detector



- Phosphor (powdered scintillator)
- Fiber-optically coupled to a CCD (2D solid-state detector) camera
- + and –
  - "general purpose"
  - radiation damage
  - area
  - phosphor
  - fiber-optic

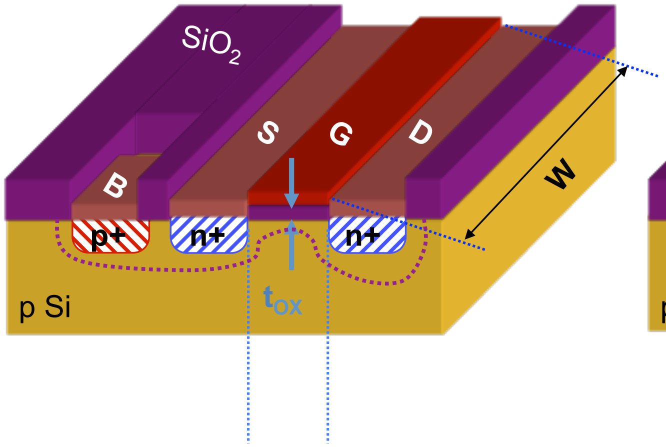
Scientific CCDs (Charge-Coupled Devices)

Dumbbell nebula - LBNL CCD
Blue: H-α at 656 nm
Green: SIII at 955 nm
Red: 1.02 mm

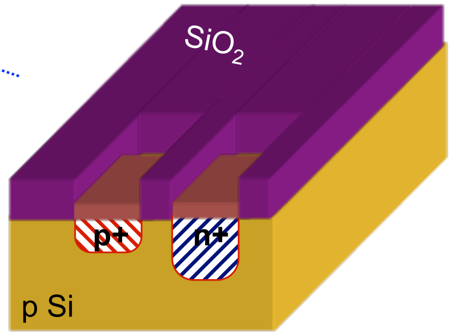
- CCD invented in 1969 by Boyle and Smith (Bell Labs) as alternative to magnetic bubble memory storage
- LST ("Large Space Telescope" – later Hubble) 1965 – how to image?
  - Film was obvious choice, but -
    It would "cloud" due to radiation damage in space
    Changing the film in the camera not so trivial
  - 1972 CCD proposed

2009 Nobel Prize in Physics

Si Processing: Integrated Circuit Elements

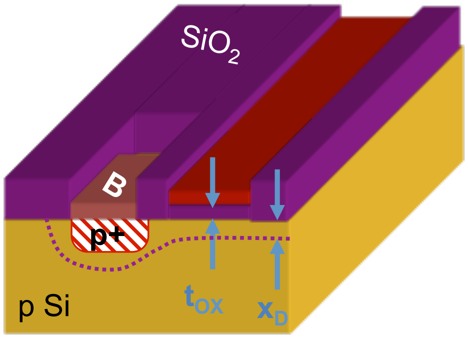


MOS Transistor



pn Diode

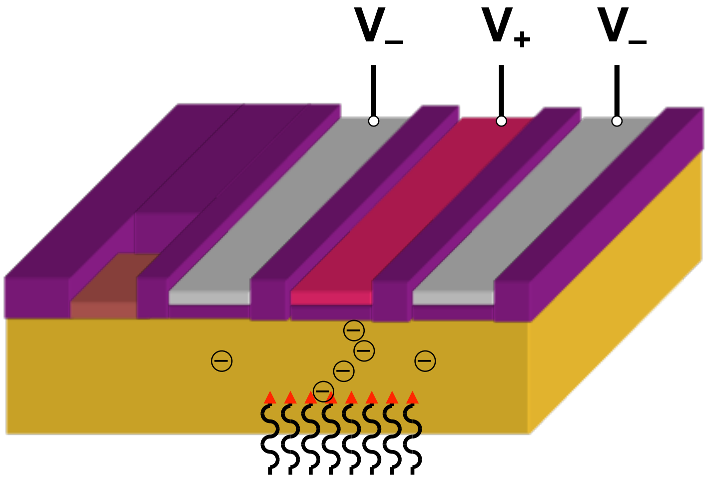
Integrated Circuit Elements



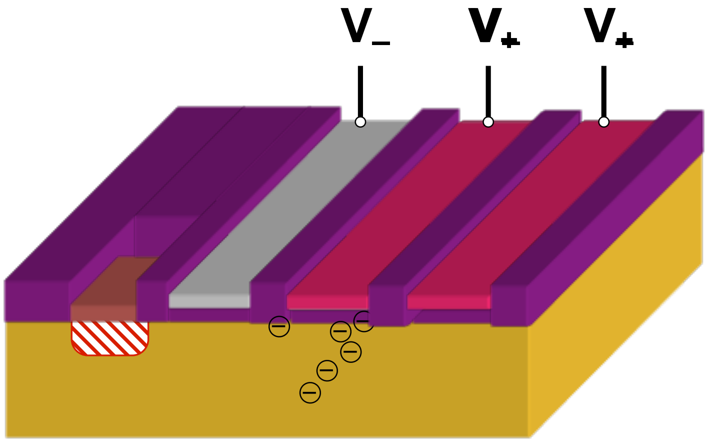
$$C = \frac{1}{\frac{1}{C_{OX}} + \frac{1}{C_{DEP}}}, \quad C_{OX} = \frac{\varepsilon_{SiO_2}}{t_{OX}}, \; C_{DEP} = \frac{\varepsilon_{Si}}{x_D}$$

MOS Capacitor

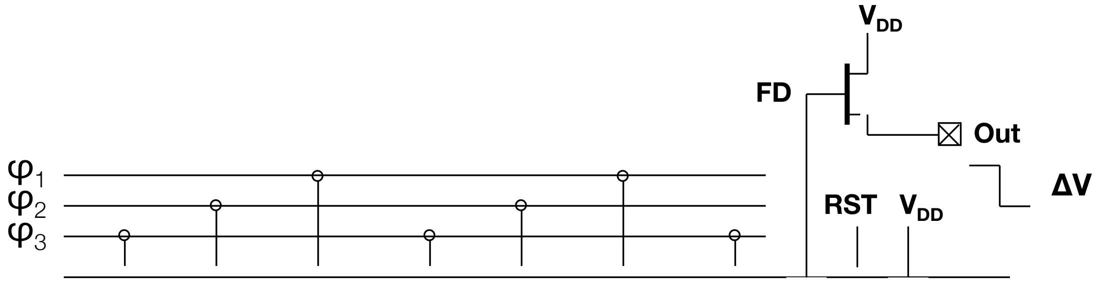
Accumulate Charge



Accumulate and Transfer Charge

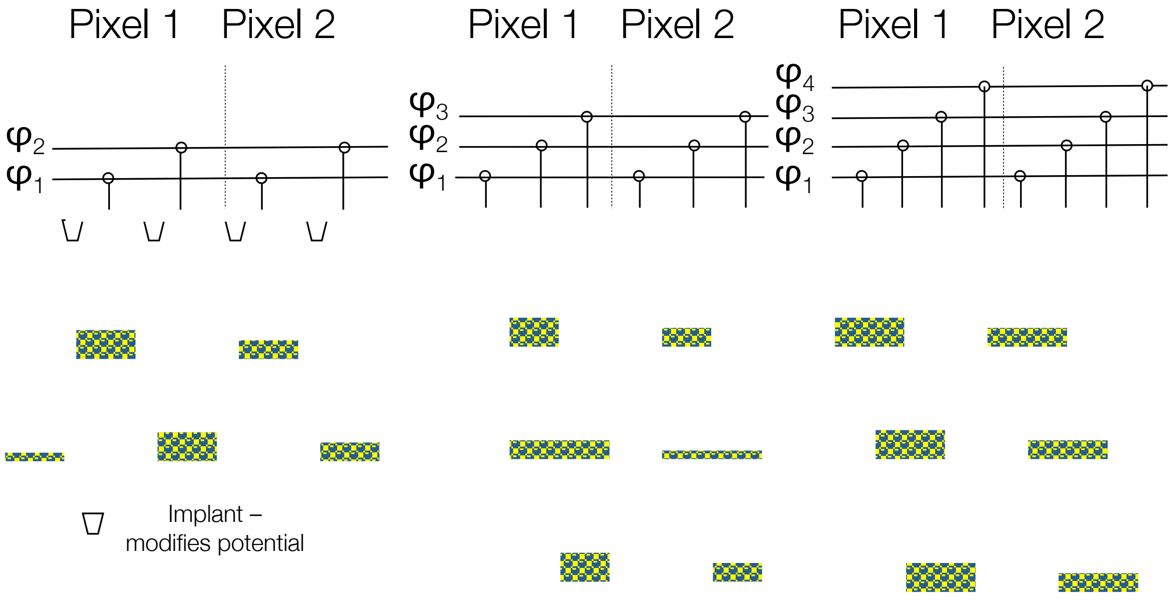


Conventional 3-Phase CCD



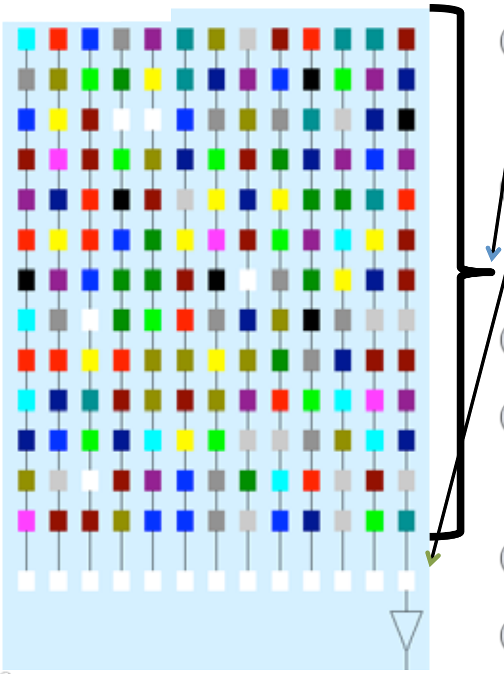
- Noiseless, ~lossless charge transfer
- High gain charge-to-voltage conversion $\Delta V = q/C_{FD}$
- Output amplifier (source follower, or …) on-chip

Many ways to do this



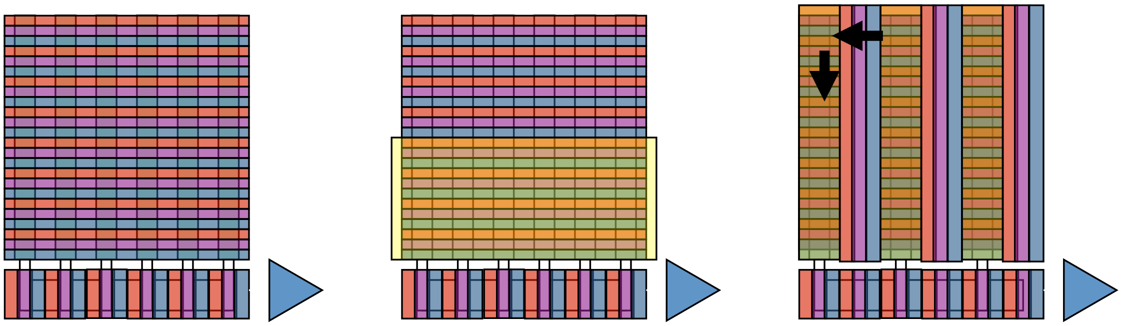
Implant – modifies potential

How it Works



- Image area – N_X x N_Y pixels
- Output shift register (N_X pixels)
- Expose image area
- Shift one row into output shift register
- Shift out each pixel
- Repeat

Several architectures

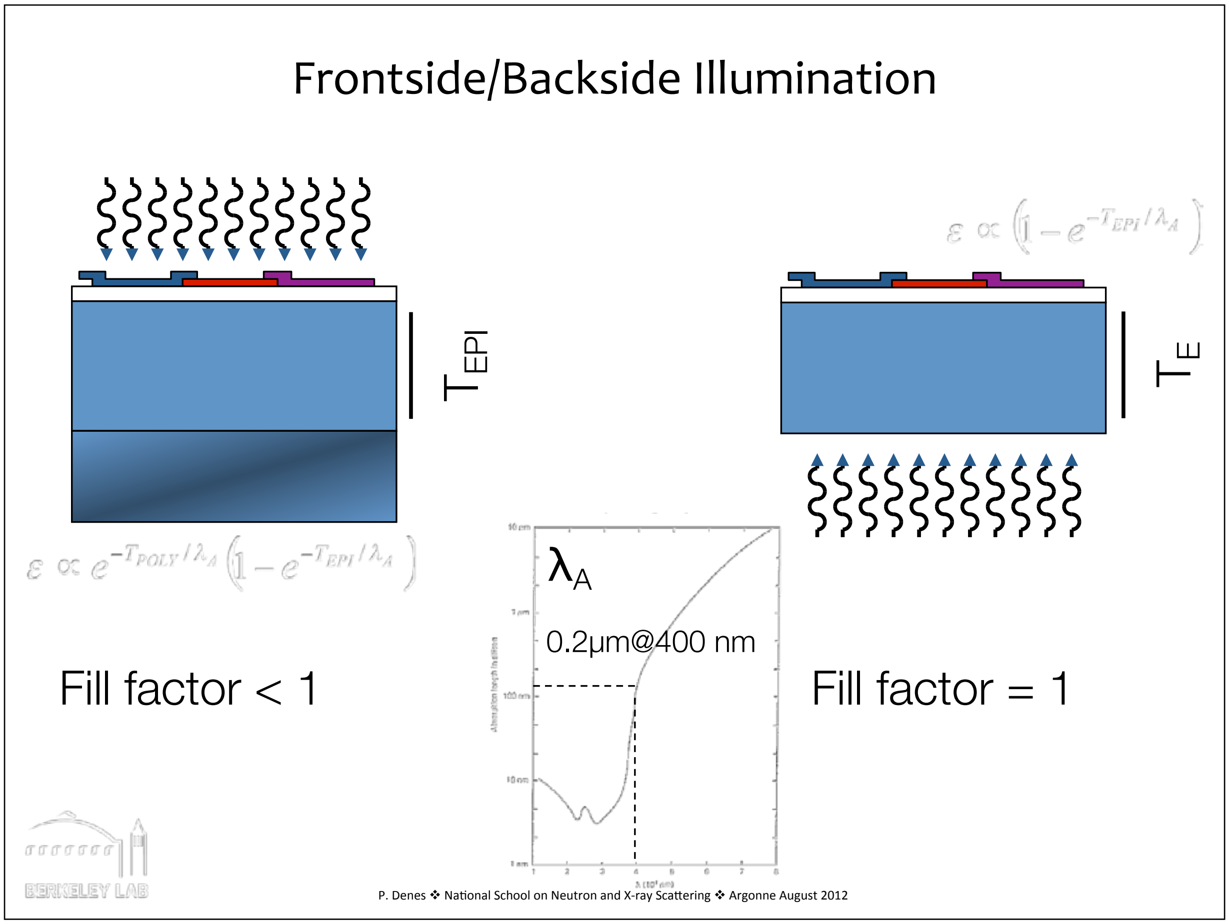


Full frame

Frame transfer

Rapid shift from image
to storage
Slower readout of
storage during integration

Interline



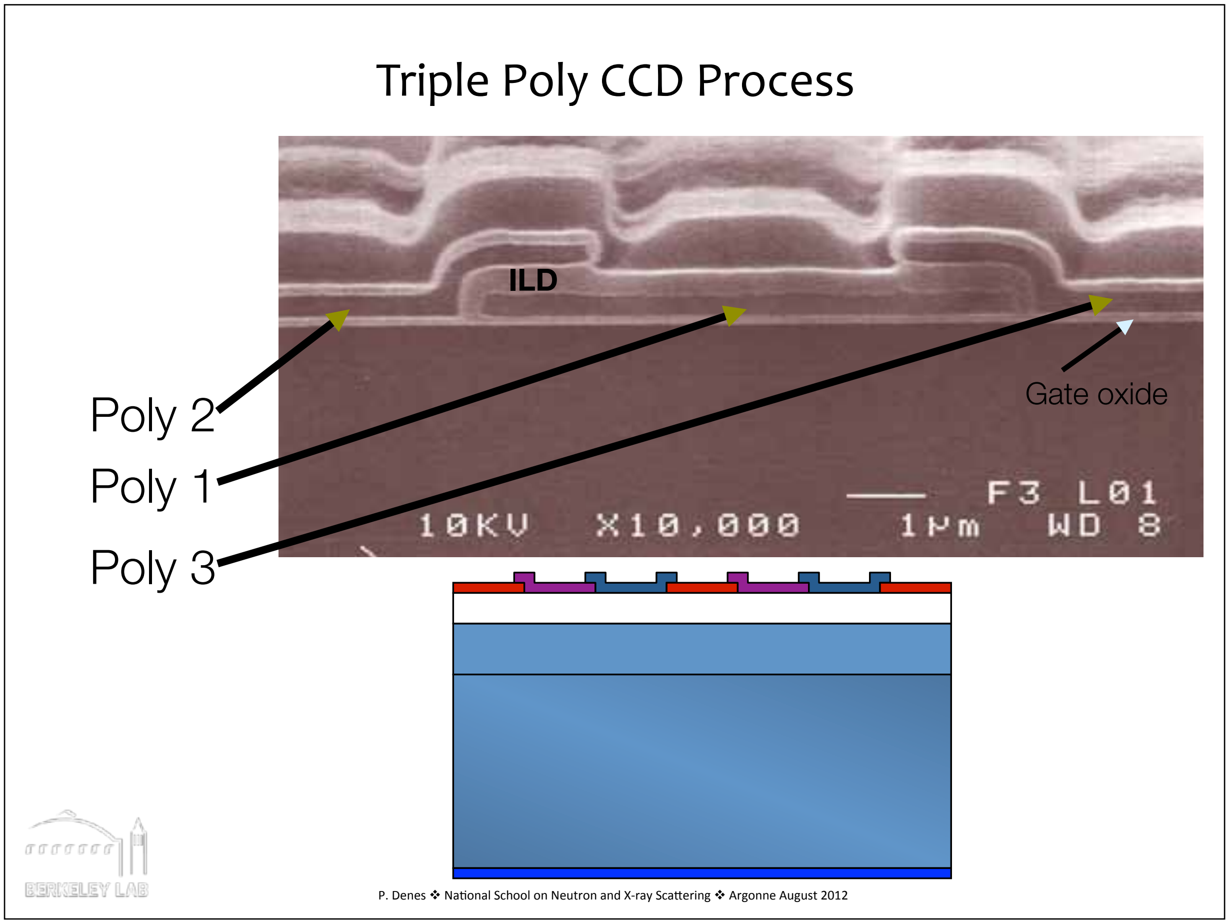
Frontside/Backside Illumination

$$\varepsilon \propto e^{-T_{POLY}/\lambda_A}\left(1-e^{-T_{EPI}/\lambda_A}\right)$$

$$\varepsilon \propto \left(1-e^{-T_{EPI}/\lambda_A}\right)$$

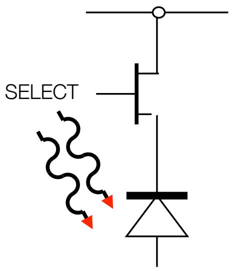
Fill factor < 1

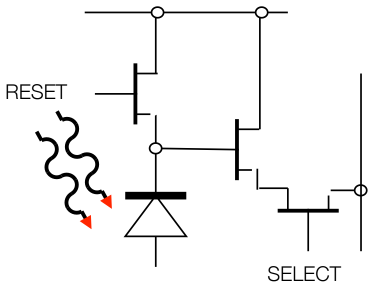
Fill factor = 1



Triple Poly CCD Process

Monolithic Image Sensors



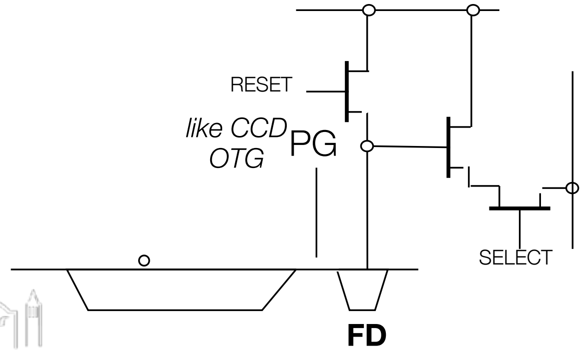


- Passive Pixel Sensor
- Proposed 1968
- No Reset, no in=pixel amplifier

- Active Pixel Sensor
- *Also* proposed 1968
- Many ways to make the photodiode

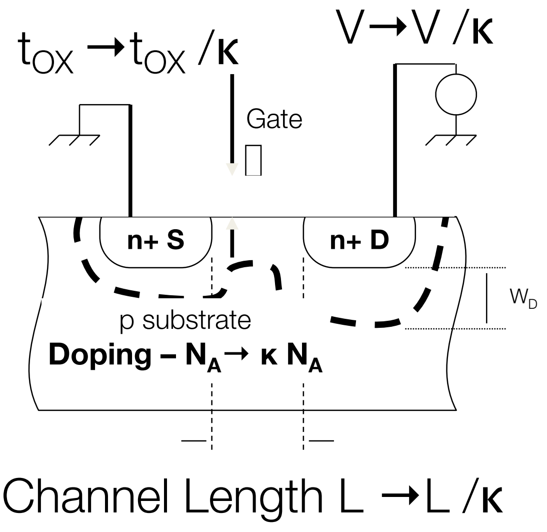
CCD vs APS

- APS – transfers a *voltage* down the column
- CCD – (noiselessly) transfers a *charge* down the column
- APS – can be more sensitive (source follower does not have to drive off-chip)
- APS – fill factor < 1 in general
- Photogate APS – like a matrix of individual CCDs
- Backside illumination – attempted for APS, work-in-progress



CMOS, CMOS "opto" and CCD processes

CMOS driven by constant field scaling

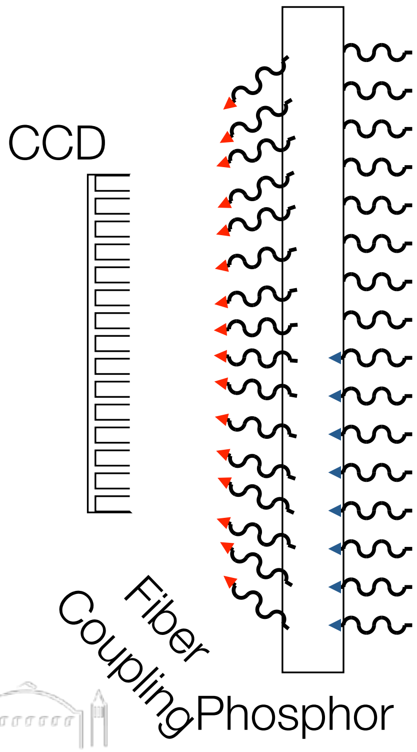


	CCD	CMOS
t_{OX} (Å)	500 - 1000	5-20
Well depth (μm)	2.5	0.5 deeper for RF
Implant (μm)	~1 channel stop	0.1 S/D implants
V	≥10	<3.3 <2.5 <1.x …
Poly layers	3 (2)	1 2 for analog
Subst. quality	Low leakage	Don't care Except opto

Why CCDs?

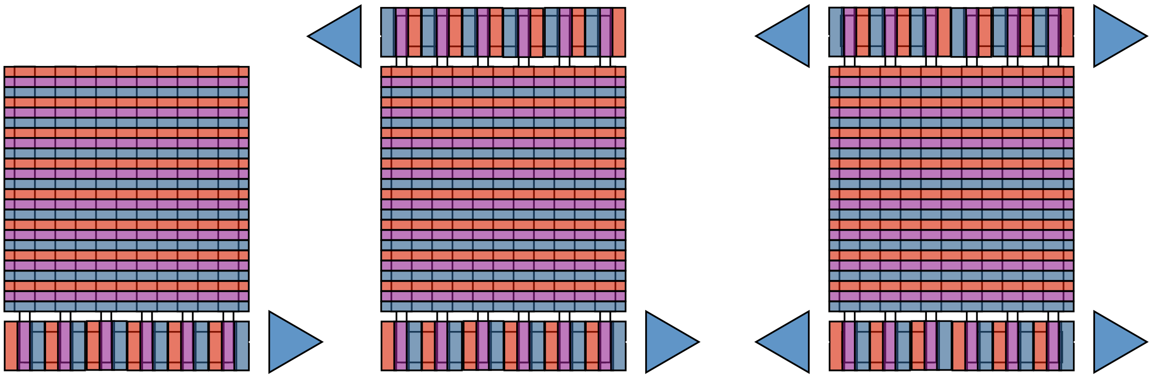
- Low noise (noiseless charge transfer, do everything to make C_{FD} small in order to get large conversion gain)
- Fill-factor = 1 (for backside illumination)
- Linear and easy to calibrate
- **Long history of scientific use**
- Large area devices easier (cheaper) to develop as CCDs than as state of the art CMOS devices
  - Readily wafer scale
- Commercially produced

“Classical” X-ray Detector



- Phosphor (powdered scintillator)
- Fiber-optically coupled to a CCD (2D solid-state detector) camera
- + and –
    - “general purpose”
    - radiation damage
    - area
    - phosphor
    - fiber-optic

CCDs are Wonderful, but SLOW



Now it gets more difficult

Increase ADC speed

$$T_f = \frac{N_V}{2}\left(T_V + \frac{1}{B_V}\left[B_H T_H + \frac{N_H}{B_H N_{port}} T_{CONV}\right]\right)$$

top+bottom readout

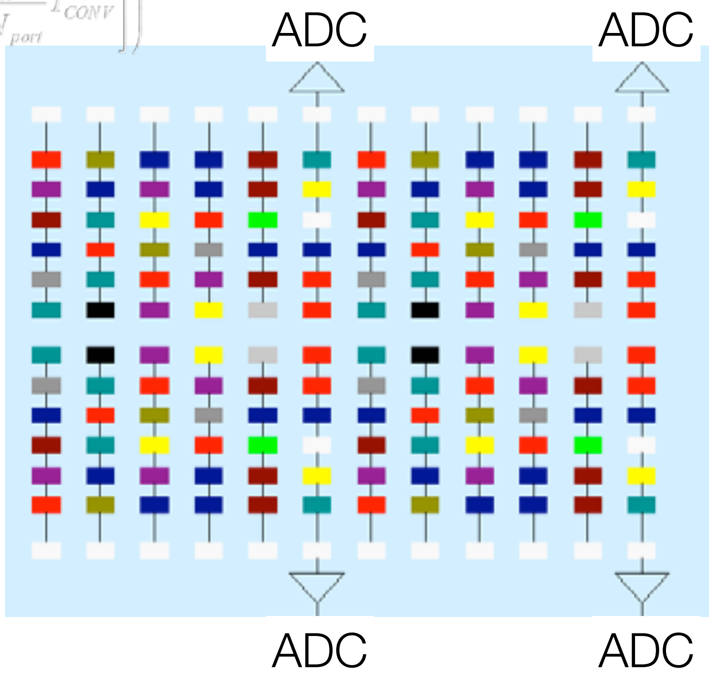
N_V, N_H = # H, V pixels

B_V, B_H = H, V binning

T_V, T_H = H, V shift time

N_{port} = # ports

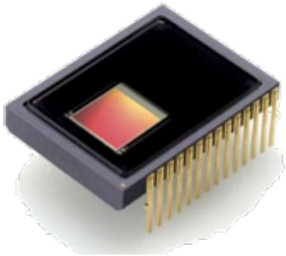
T_{CONV} = total conversion time including reset, summing well, …



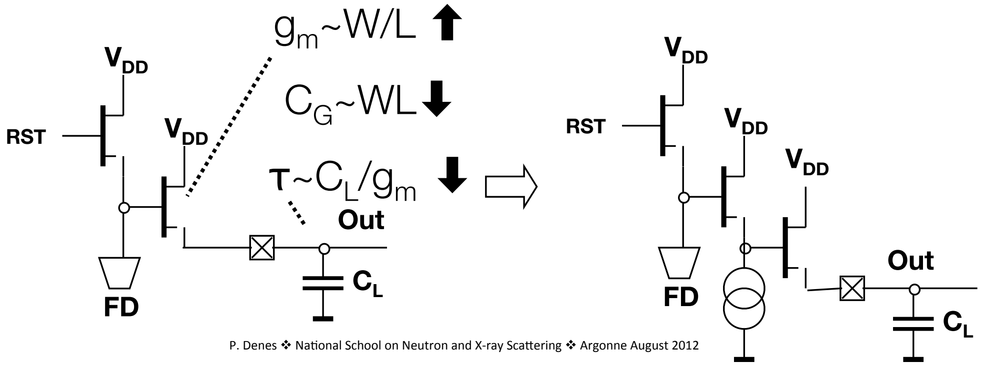
For example

Increase readout/ADC speed

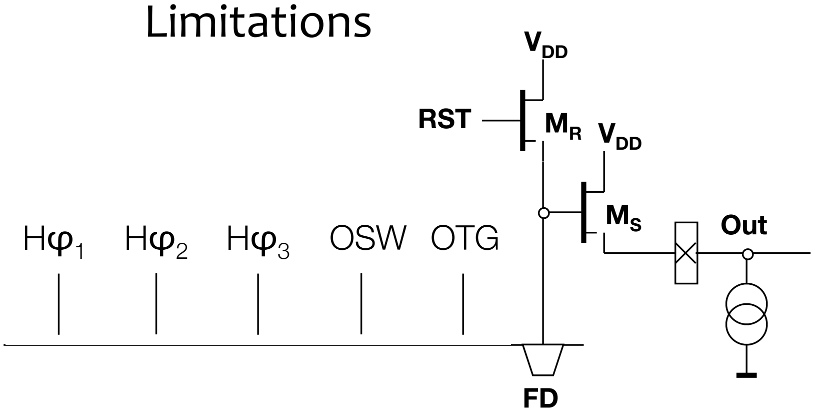
- Dalsa – FT50M
- 1024 x 1024 x 5.6 µm pixel
- Frame transfer / 2 ports
- 100 fps = 100 MPix/s
- 11.1 bits [67 dB] at 30/60 fps
- 10.1 bits [61 dB] at 50/100 fps



S/F Limitations



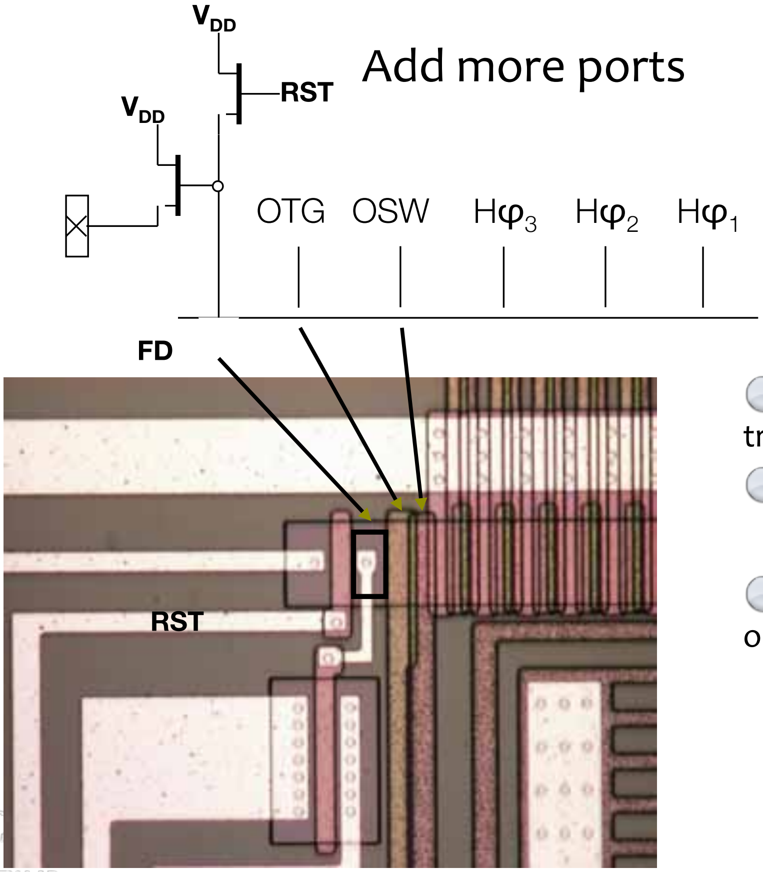
Limitations



- √kTC Noise contribution from M_R (reset switch) removed by CDS (correlated double sampling – measure V_R and $V_R + V_S$)
- Noise contributions from M_S (source follower)
  - Thermal noise $V_n^2 \sim 4kT\gamma g_m \int H^2(f)\, df$
  - 1/f noise $V_n^2 \sim \frac{K}{C_{ox}WL} \int H^2(f) \frac{1}{f}\, df$
  - Noise from current source

⬆ ~ √rate

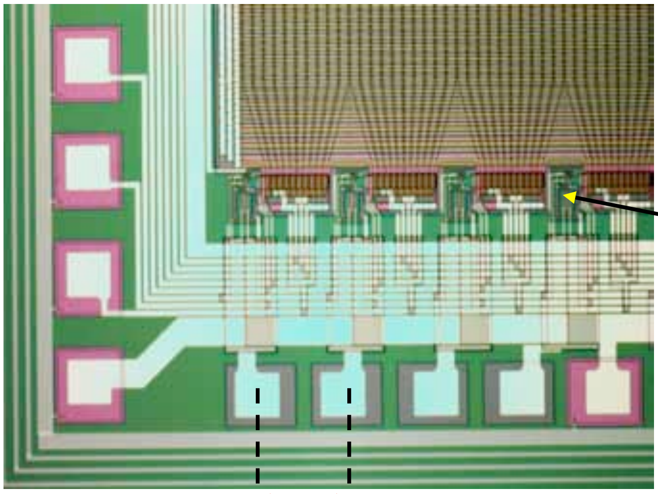
Add more ports



- Reset and output transistors need room
- Want to minimize C_{FD}

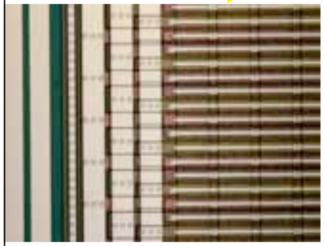
- Need space for the output stage!

(almost) Column-Parallel CCD

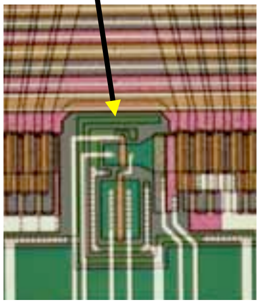


Constant
Area
Taper
Mini-shift reg.
Output stage

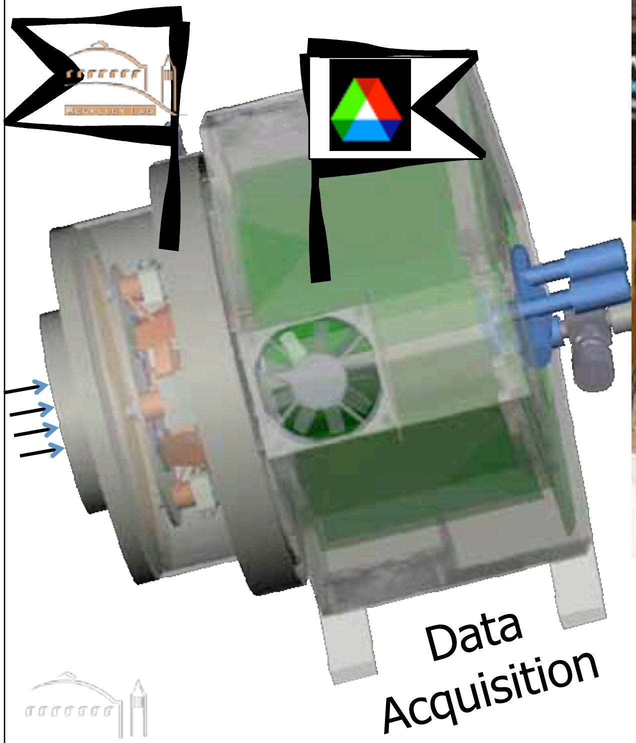
Mini-SR with taper
Metal strapping



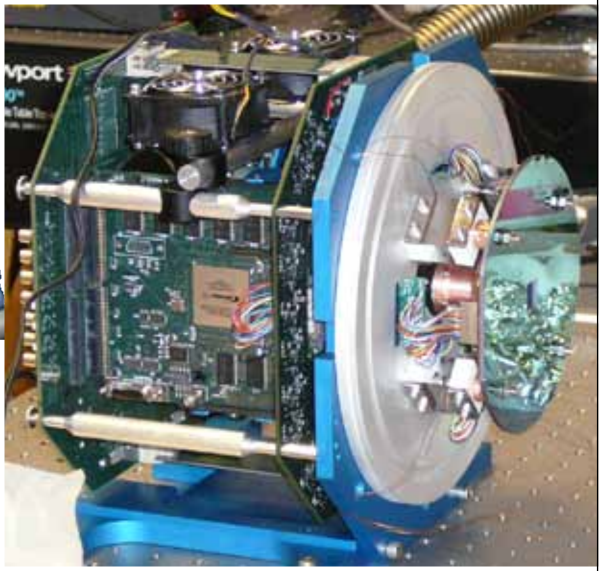
~300 µm pitch
bond pads
(wire-bondable)



ALS / APS Collaboration

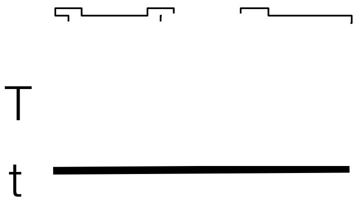


Data
Acquisition



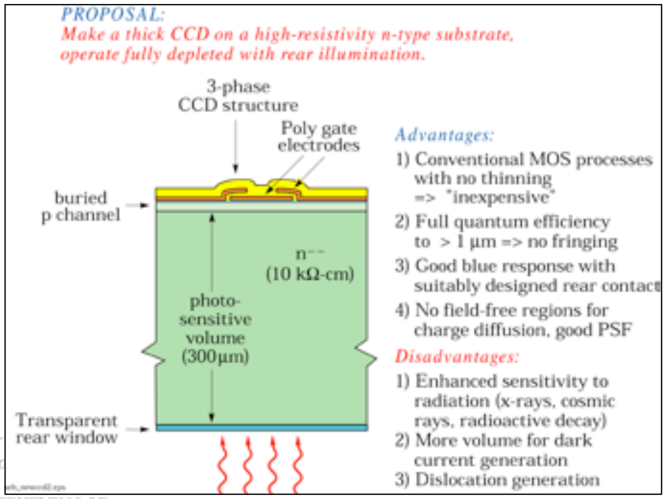
Direct Detection

Previous example of CCD usage was for optical photons. What about x-rays?



This should be depleted – generally thin with conventional processes

→ add a layer which can be used as an electrode


PROPOSAL:

Make a thick CCD on a high-resistivity n-type substrate, operate fully depleted with rear illumination.

Advantages:

1) Conventional MOS processes with no thinning => "inexpensive"
2) Full quantum efficiency to > 1 μm => no fringing
3) Good blue response with suitably designed rear contact
4) No field-free regions for charge diffusion, good PSF

Disadvantages:

1) Enhanced sensitivity to radiation (x-rays, cosmic rays, radioactive decay)
2) More volume for dark current generation
3) Dislocation generation

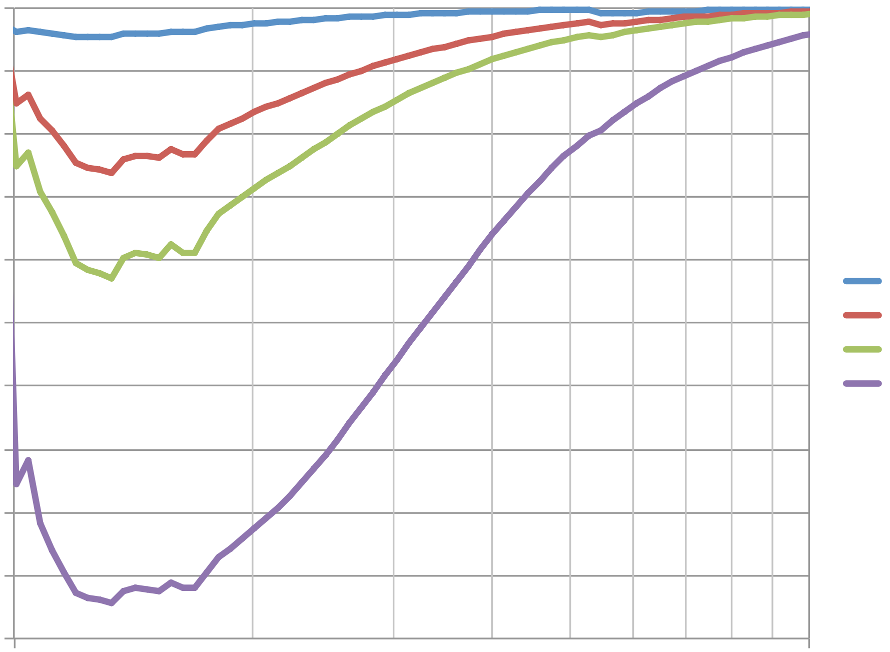
LBL CCD – S. Holland et al.

Detector Thickness to Collect 99% of Photons

T

Hard X-ray challenges

Thin “window” for Soft X-rays



t

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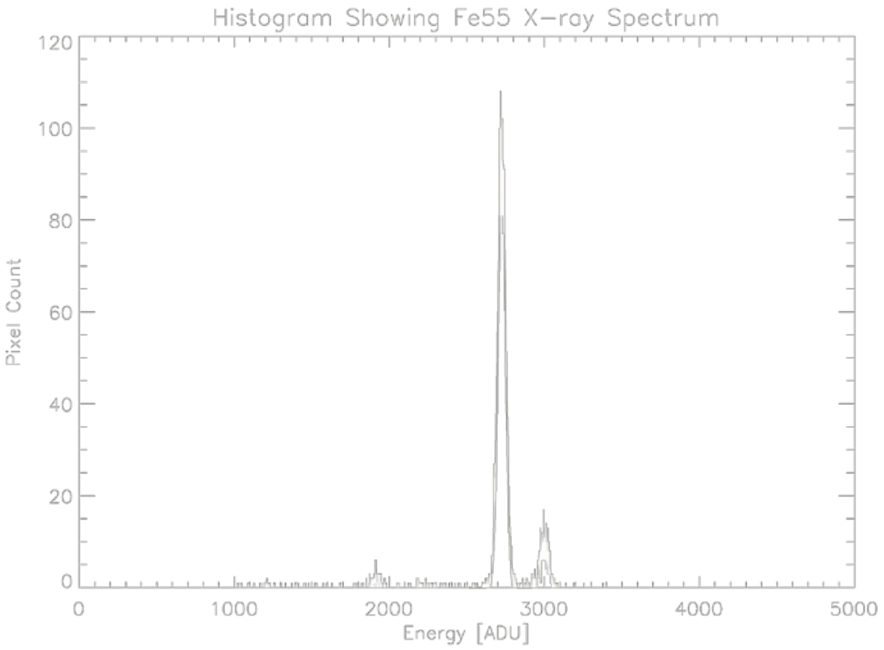
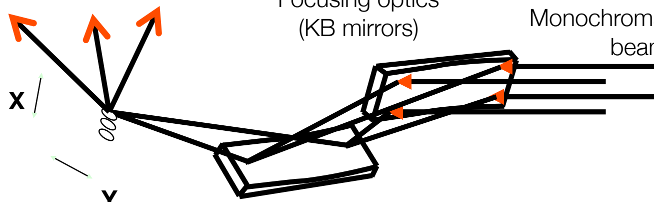
650 µm thick CCD

^{55}Fe K_{α} and K_{β}. Resolution ~ 126 eV at 5.6 keV

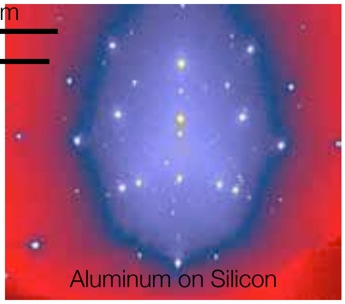


Example: X-Ray microdiffraction at the ALS

- Sample is raster-scanned under a submicron-sized white (or monochromatic) X-ray beam focused by Kirkpatrick-Baez mirrors. At each step a diffraction pattern is recorded.
- Analysis of the diffraction pattern scans provides with phase distribution, crystal orientation maps, strain/stress maps, dislocation structure and distribution
- The technique helps understanding the complexity of the micromechanics of materials (strength, resistance to failure, …) at granular and subgranular level

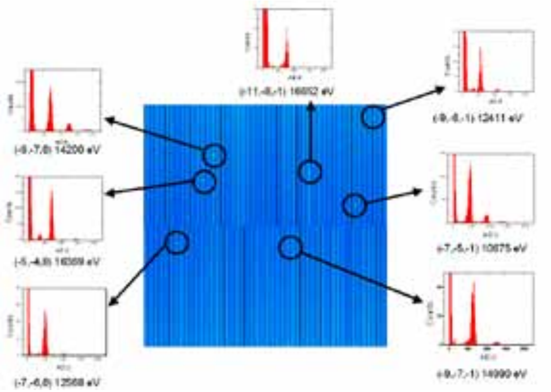


- No sample rotation required !



Laue pattern captured by a X-Ray CCD detector

Microdiffraction

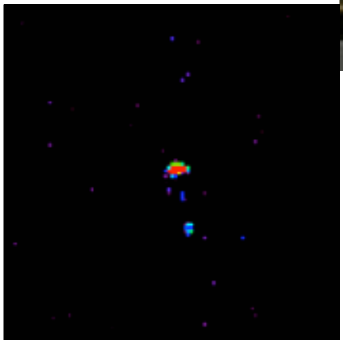


hours ➔ seconds

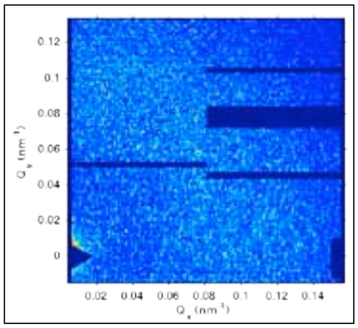
KTP crystal indexed. The energy of each reflection can be measured …

⇒ Laue ab-initio indexation (of unknown structures, heterogeneous samples, …)

⇒ Energy-resolved Laue diffraction for structure solution using Laue (pb of harmonics, scaling,…)

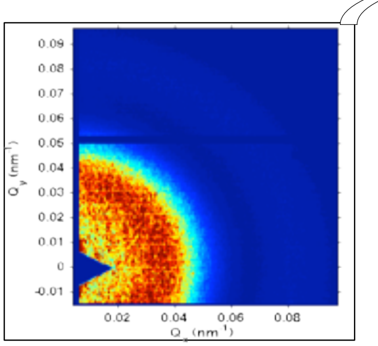


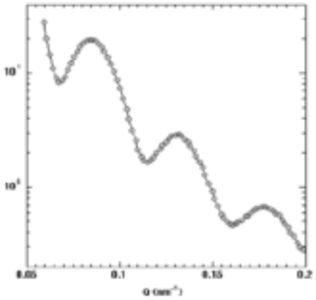
Example: XPCS at APS BL 8-ID

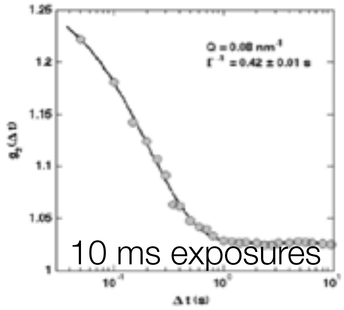


FastCCD at 8-ID

time autocorrelation







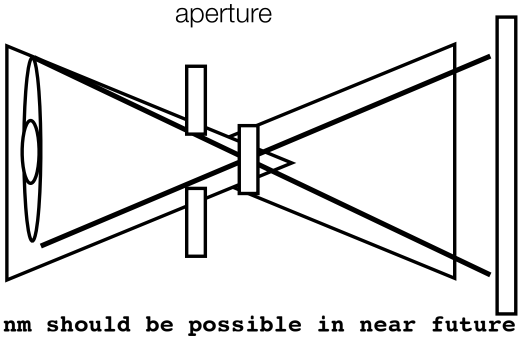
10 ms exposures

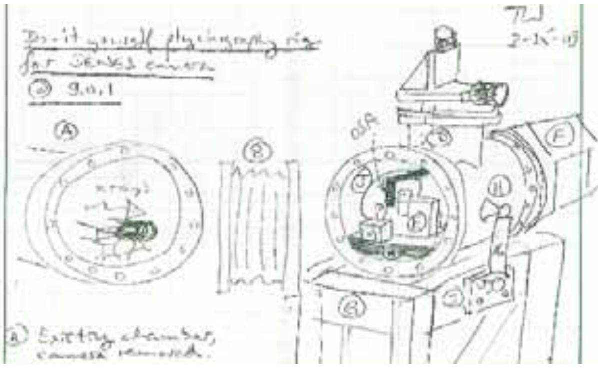
time average

XPCS Example – 71nm radius latex spheres in glycerol at ~-20 deg C

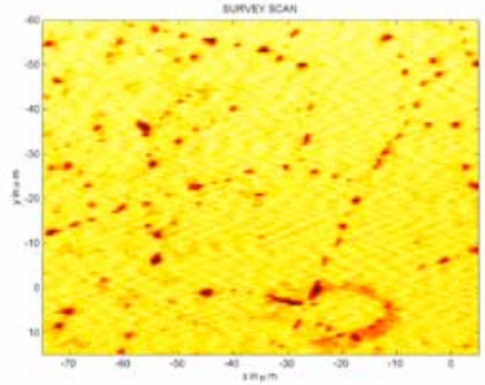
(Data courtesy of Suresh Narayanan and Alec Sandy)

Example: Coherent Imaging at ALS BL 9.0.1



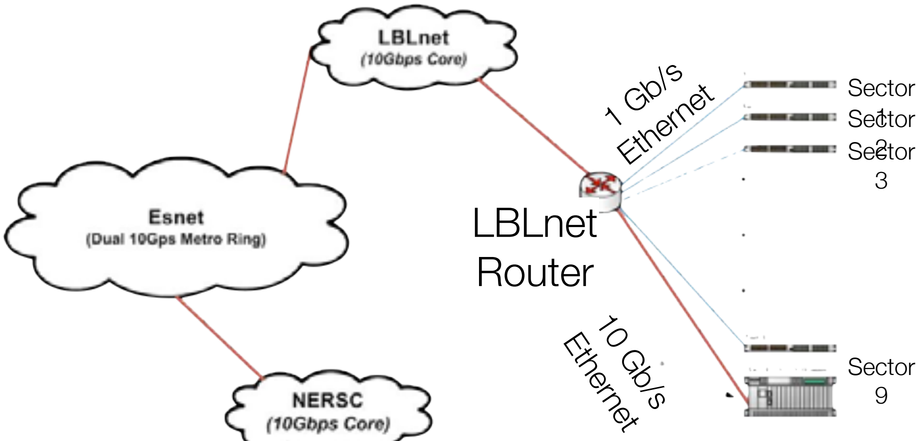


10 nm should be possible in near future



Soft X-ray Ptychography

Fast Readout = Lots of Data


LBLnet (10Gbps Core)

Esnet (Dual 10Gps Metro Ring)

NERSC (10Gbps Core)

1 Gb/s Ethernet

LBLnet Router

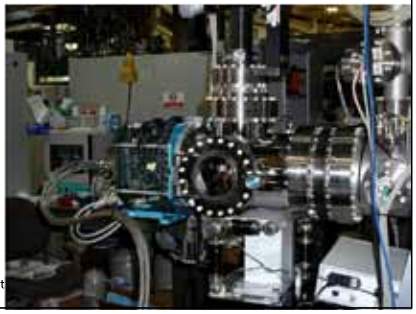
10 Gb/s Ethernet

Sector 1

Sector 2

Sector 3

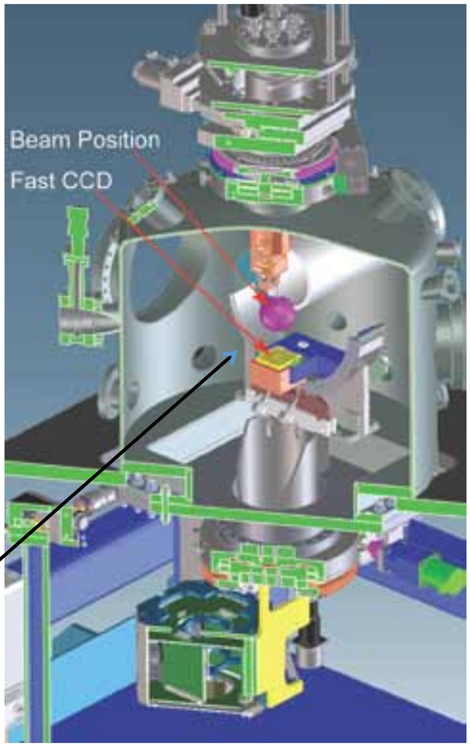
Sector 9

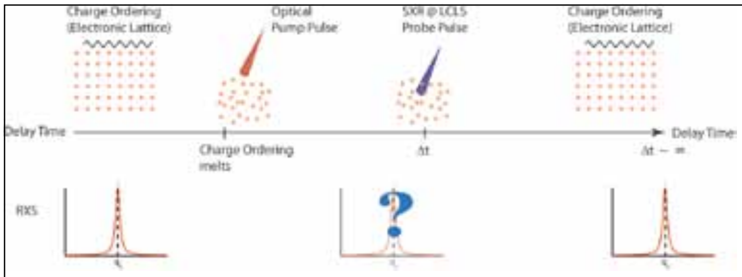


Phase 1 - ATCA to LBLnet
Phase 2 - Install multiport
10 Gb/s switch at Sector 9

RSXS End Station for LCLS Hutch 2

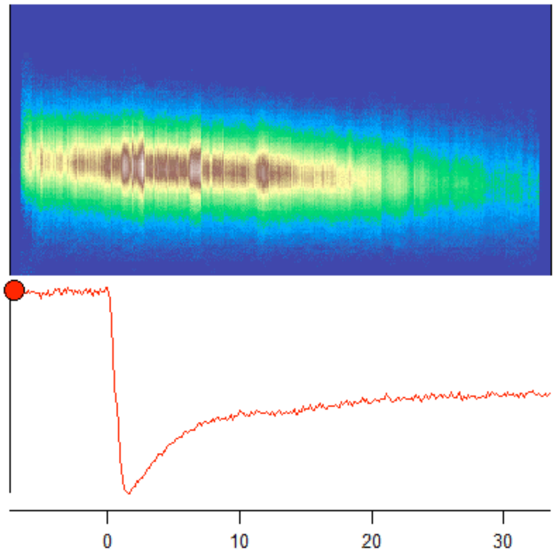
Goniometer
360° horiz.
100° vert.





LCLS SXR

Fast melting and slow recovery of
spin ordering around 50K
(correct time jittering and intensity fluctuation)

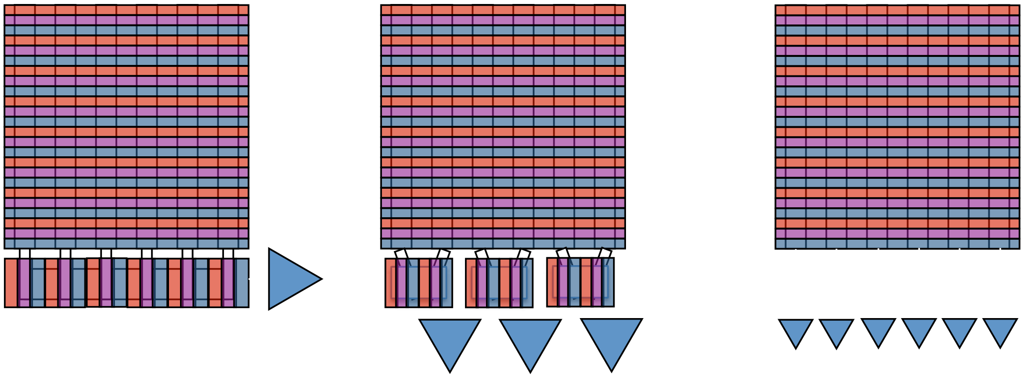


CCD ➔ fCCD ➔ vfCCD

Conventional CCD
10^0 Hz

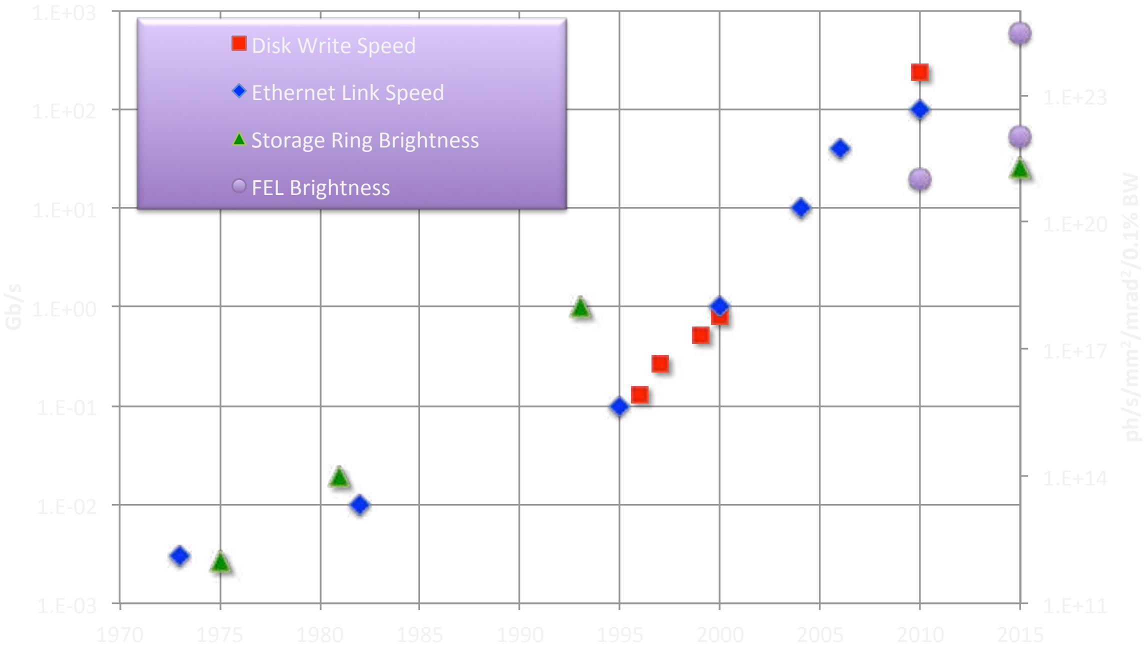
(a)CP-CCD
10^2 Hz

CP-CCD
10^{3-4} Hz

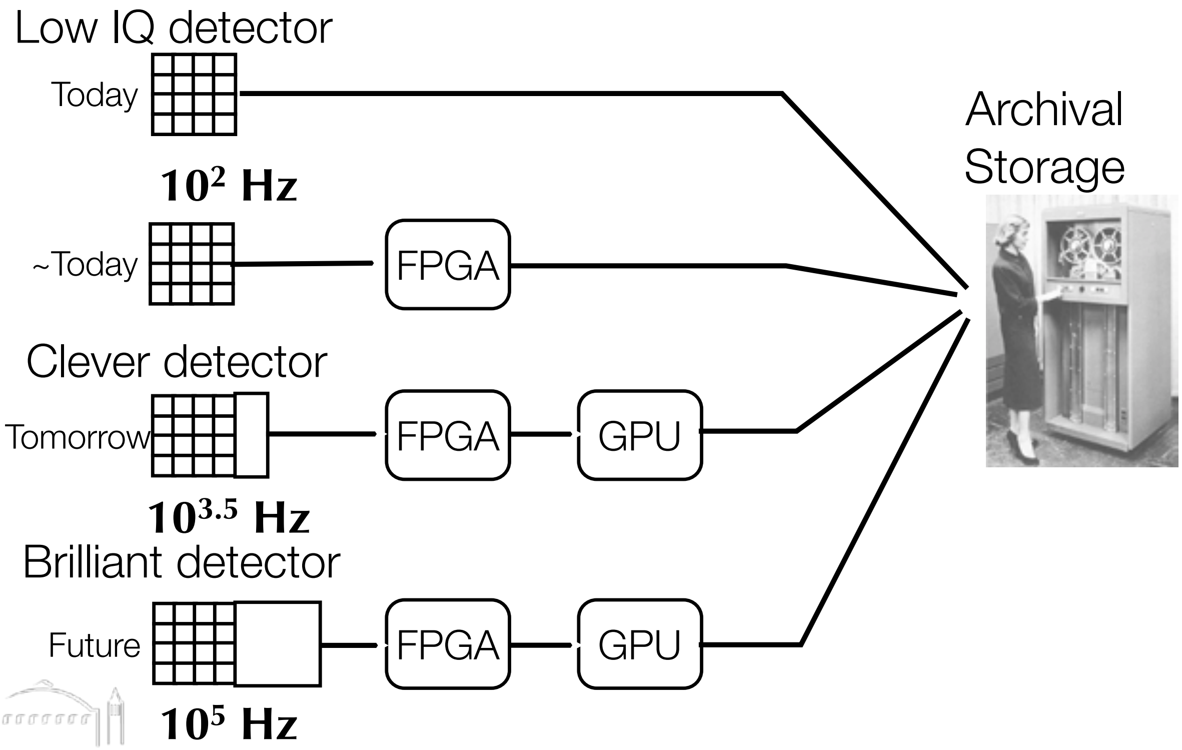


Conventional CCD	FastCCD	Very FastCCD
4-port	(almost)Column Parallel	Column Parallel
Commercial readout	*fCRIC* (custom 0.25 μm CMOS readout IC)	*HIPPO* (custom 65 nm CMOS readout IC)

Data Acquisition, Transmission and Processing



Future developments in processing



Low IQ detector

Today

10^2 Hz

~Today

FPGA

Clever detector

Tomorrow

FPGA

GPU

$10^{3.5}$ Hz

Brilliant detector

Future

FPGA

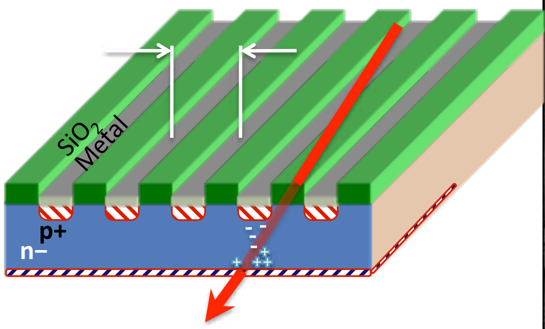
GPU

10^5 Hz

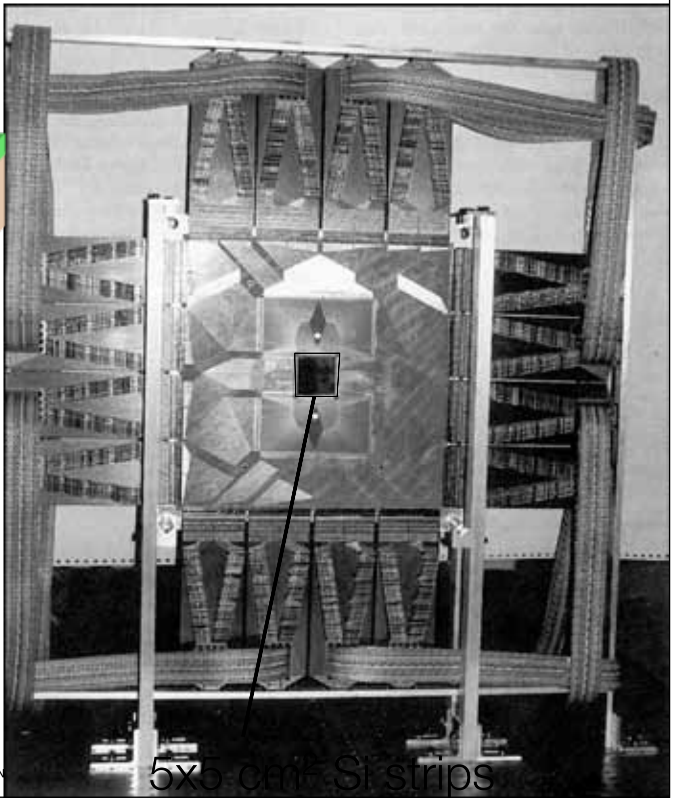
Archival Storage

Microelectronics-enabled Detectors

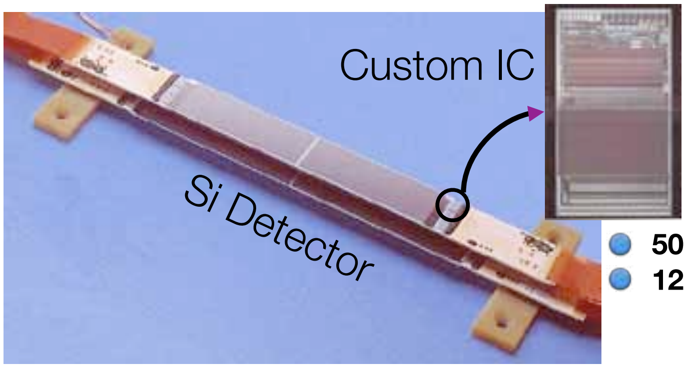
Silicon strip detector



Silicon strip detector (1D)
for particle physics ca. 1984

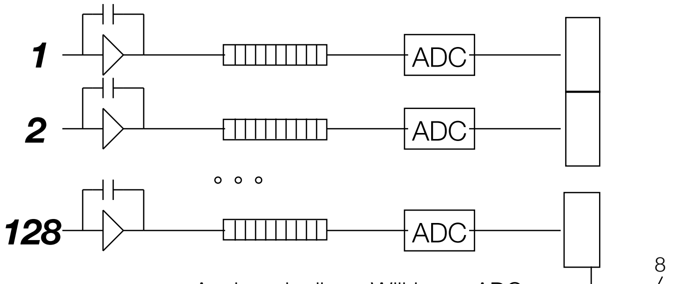


Followed by Custom ICs



- **50 µm pitch**
- **128 channels**

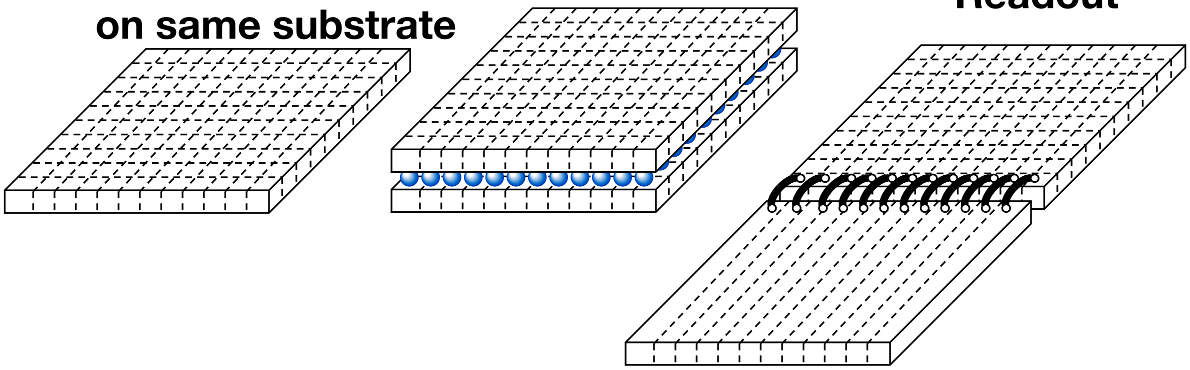
Charge sensitive
amplifier with
adjustable risetime



Analog pipeline Wilkinson ADC

Zero-suppressed
readout on 8-bit
parallel bus

Further Options



Monolithic sensor+readout on same substrate

Hybrid

Sensor + Readout

2D segmented Si

2D segmented Si attached to 2D segmented Si

2D segmented Si attached to 1D segmented Si or other electronics

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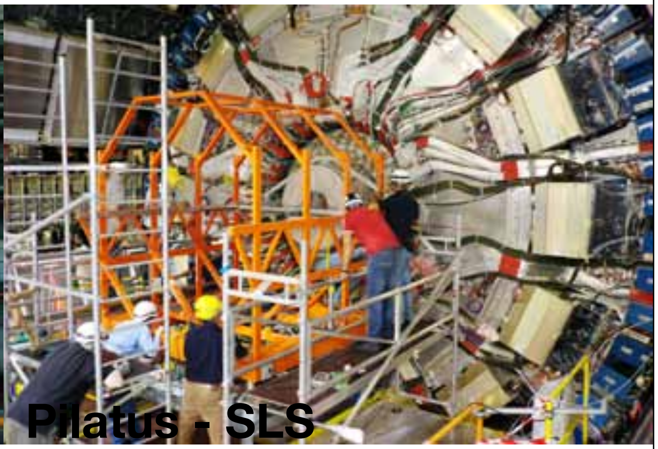
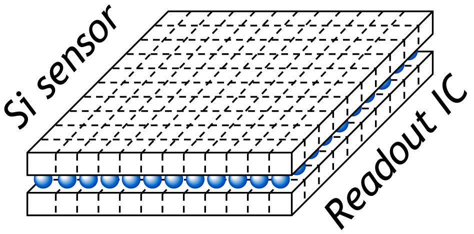
LHC Pixel Detectors

CMS

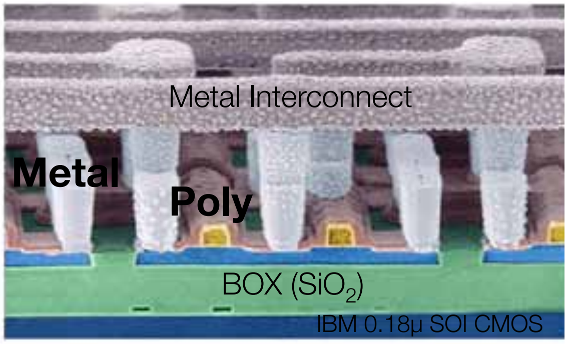


ATLAS

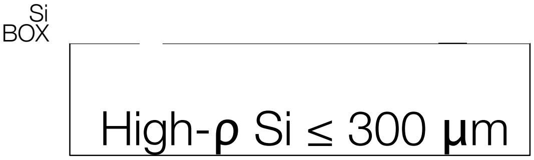
Large projects to develop hybrid pixels

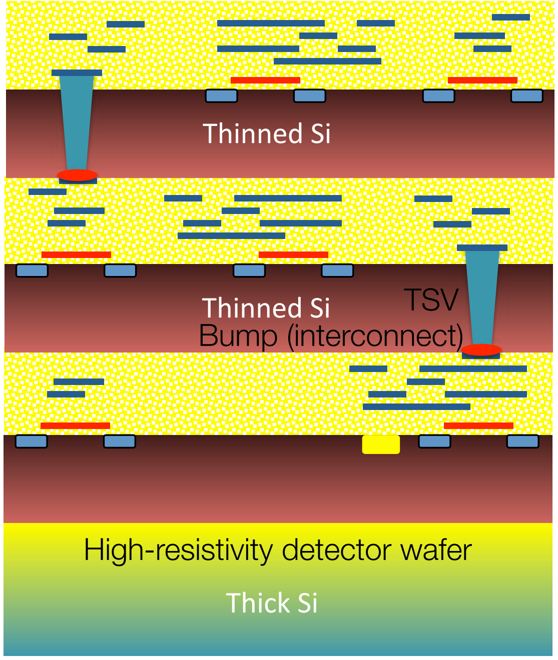


R&D: SOI and 3D Integration

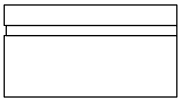
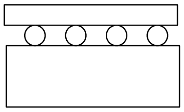
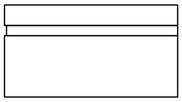
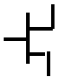


Oki SOI Process (KEK)



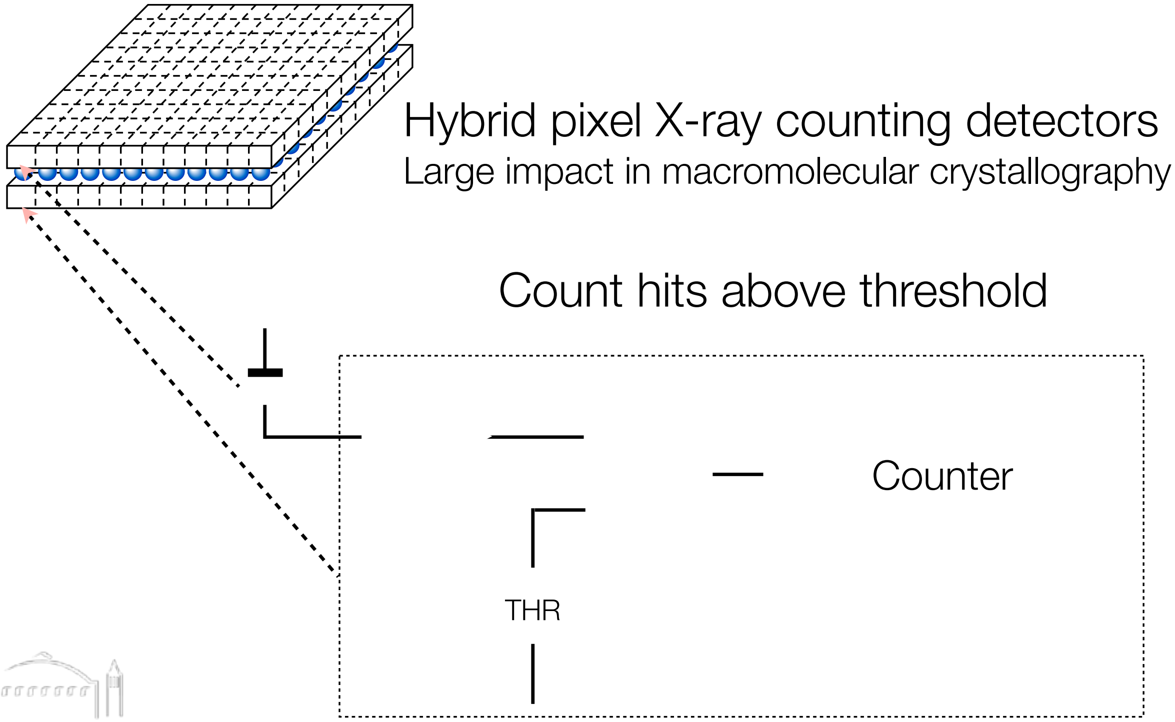


(Direct Detection) Pixel Complexity

	CCD on thick, high-ρ Si	SOI on thick, high-ρ Si	Hybrid on thick, high-ρ Si	3D on thick, high-ρ Si
				
Size	$10^2 - 10^3$ µm^2	$10^2 - 10^3$ µm^2	10^4 µm^2	10^2 µm^2
 /pix	0	$10^1 - 10^2$	$10^2 - 10^3$	$10^1 - 10^2$
ENC	$10^0 - 10^1$ e^-	10^1 e^-	10^2 e^-	?

Disclaimer: ALS is a soft x-ray facility – ideal for Si (except for noise!)

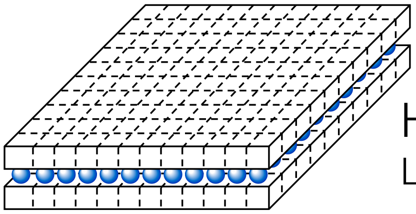
A parting, practical example



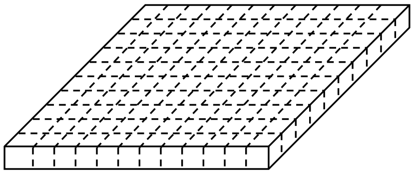
Hybrid pixel X-ray counting detectors
Large impact in macromolecular crystallography

Count hits above threshold

A parting, practical example

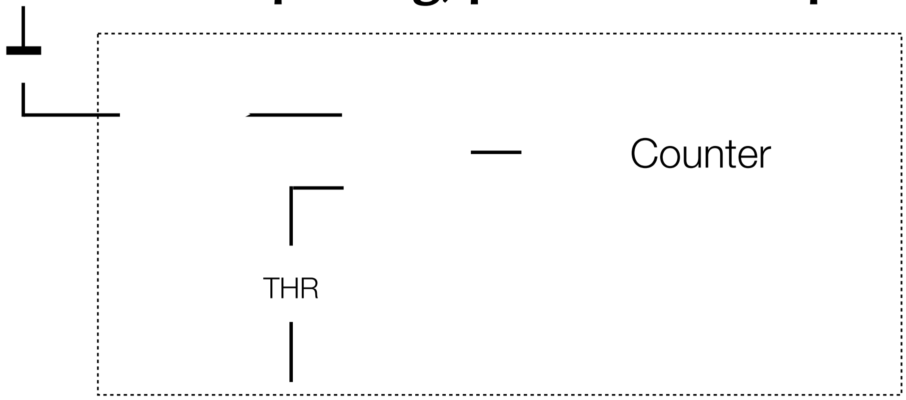


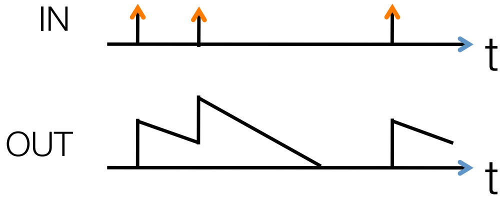
Hybrid pixel X-ray counting detectors
Large impact in macromolecular crystallography



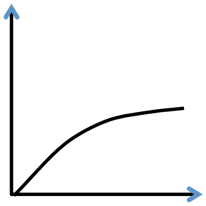
❶ Silicon (in standard microelectronic thicknesses) starts to become transparent above 8 keV
➜ Search for better sensors
(hard to beat silicon)

A parting, practical example





❷ Count rate limitations ➜ lose hits above a certain rate ➜ “rate correction”



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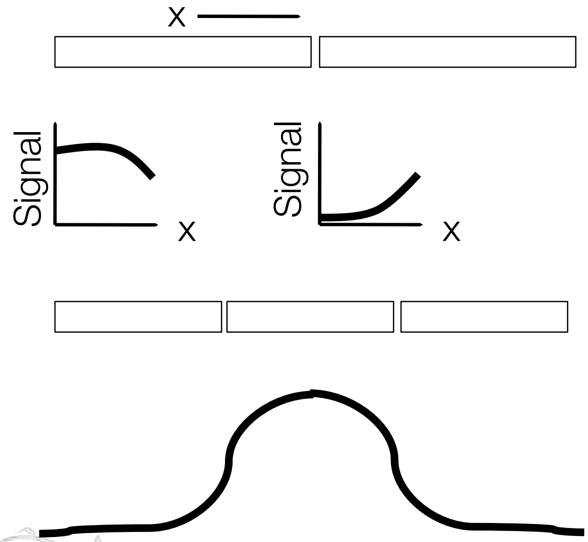
❸ Pixel Size, Diffusion and Analog vs. Digital

Even a fully-depleted detector will have 5 – 10 μm RMS diffusion
(so there will be some charge sharing)



2 “large” digital (counting) pixels

Some region (depending on diffusion σ) where counting is complicated (double count? missed counts?)

3 “small” analog pixels

Diffusion spreads charge across pixels – but center-of-gravity can give sub-pixel (μm) position resolution
(while adding noise!)

Summary (1)

- For a detector, the only useful thing a photon can do is create an electron
  - Note to accelerator people: the only useful thing an electron can do is create a photon
- Detection mechanisms
  - "Direct" (includes film, image plates, …)
  - "Indirect" – usually via scintillator
- Sensor "properties" critical
  - Density (stopping power, σ_{PE}, …)
  - Band gap, light yield, …

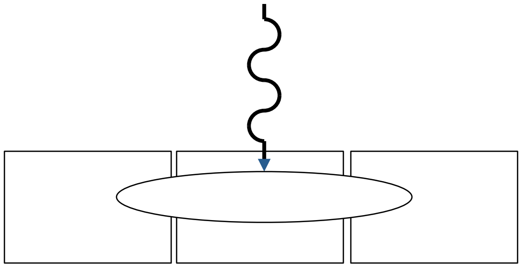
Summary (2)

- Like parking spaces, "no lack of detectors, only lack of imagination"
  - Microelectronics-enabled detector development in particle physics starting to spill over into synchrotron radiation research
- Semiconductor detectors!
- DAQ, computing and processing!
- Si excellent for E < 10 keV (and benefits from commercial processing)
  - Other developments, e.g. involving avalanche multiplication, that there was no time to discuss
  - For higher energies, have candidate materials (GaAs, Ge, CdTe, …) but need R&D
- Future will be detectors designed for experiments (not experiments designed for detectors)

Summary (3)

- Fluctuations
  - $0 \le E_e \le E_\gamma$ in “detector”
  - Number ($N \propto E_e$) of secondary (tertiary) particles
  - Electronic noise
    - Thermal
    - Faster is (generally) noisier
- Spatial resolution (PSF, MTF) (diffusion)
- Temporal resolution (noise is important)
- DQE
- Radiation damage (not discussed, but important)

In other words

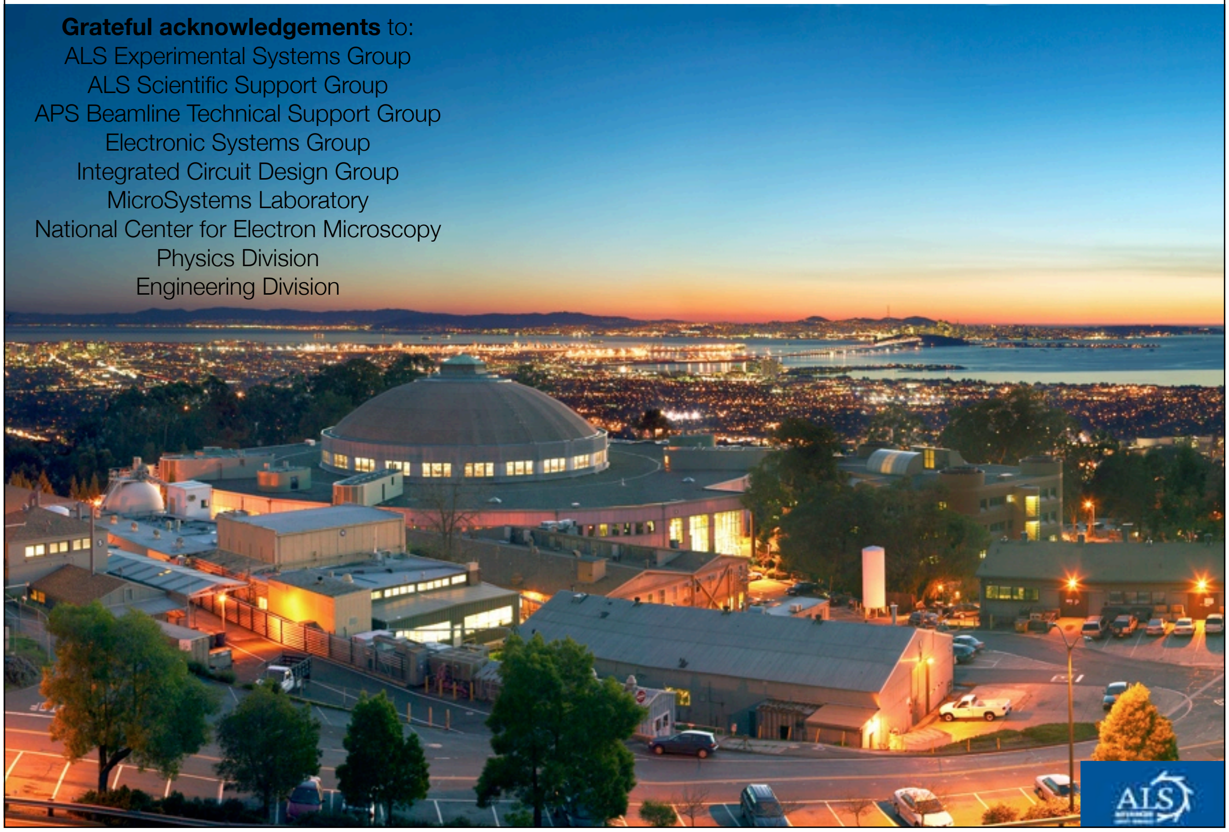


- Photon incident at (0,0)
  - Probability Q.E. of creating a detectable* signal
  - Signal $\propto 1/\eta$
    - Photostatistics
    - Fano factor
  - Spatial resolution (PSF, MTF) (diffusion)

- *Detectable = f(Electronics)
  - DQE ~ 1/ [Electronic] Noise
- $\sigma(E) \sim F \oplus$ Noise
- $\sigma(t) \sim$ Noise

Understand the physics of detection
What you get is what you see
What (how) you see is complicated

Questions?



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