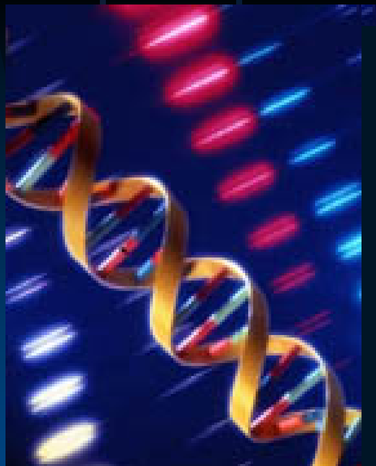


PerkinElmer™
precisely.

Si APDs
for X-Ray detection

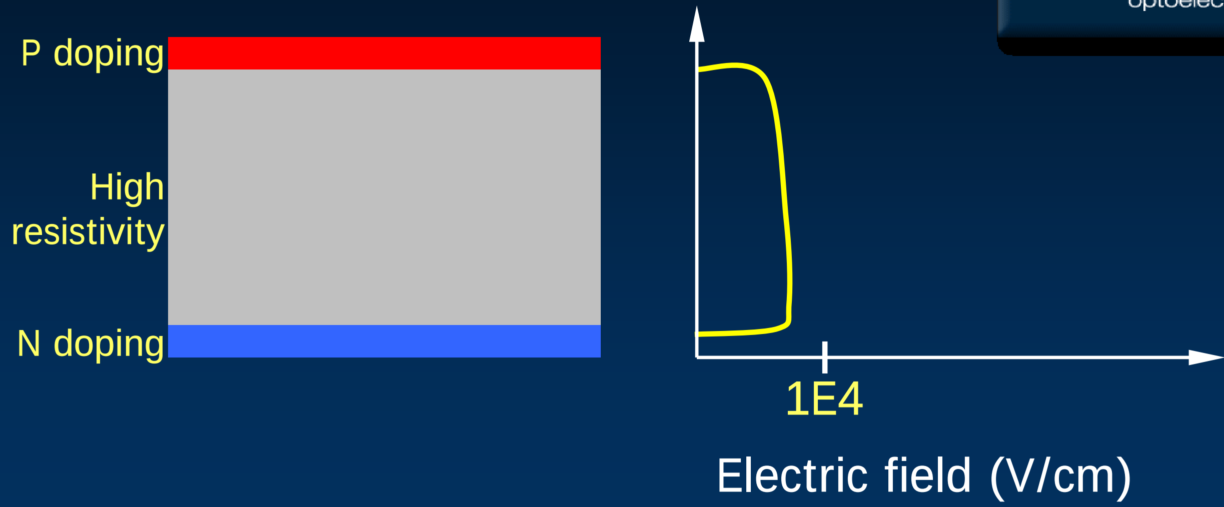
Talk Outline.

PerkinElmer™ optoelectronics.

- Avalanche PhotoDiodes ...
  - Schematic
  - Basic principles (gain, signal, noise)
  - Types / Manufacturers.
- Energy resolution
- Timing resolution/Efficiency
- Arrays
- Developments.

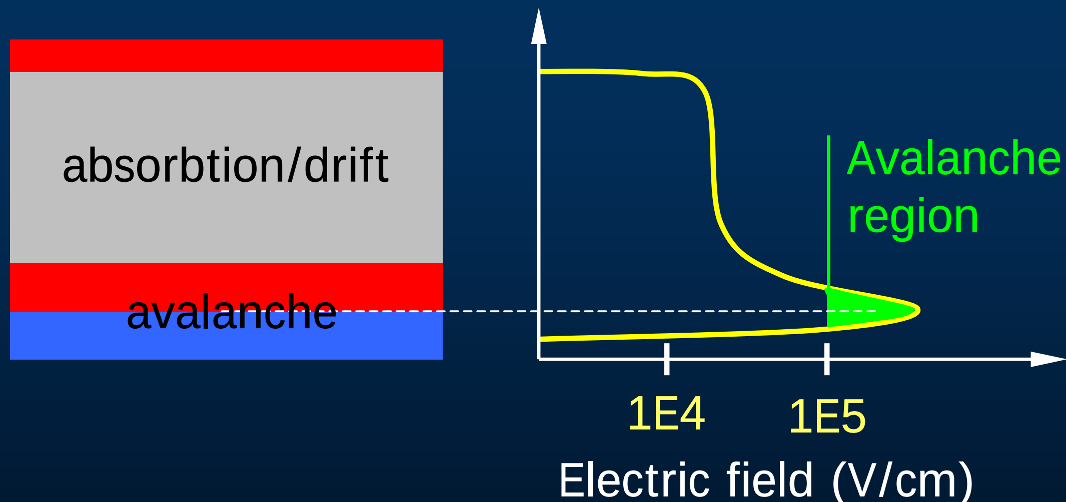
Avalanche Photo-Diode schematic

PIN diode



APD

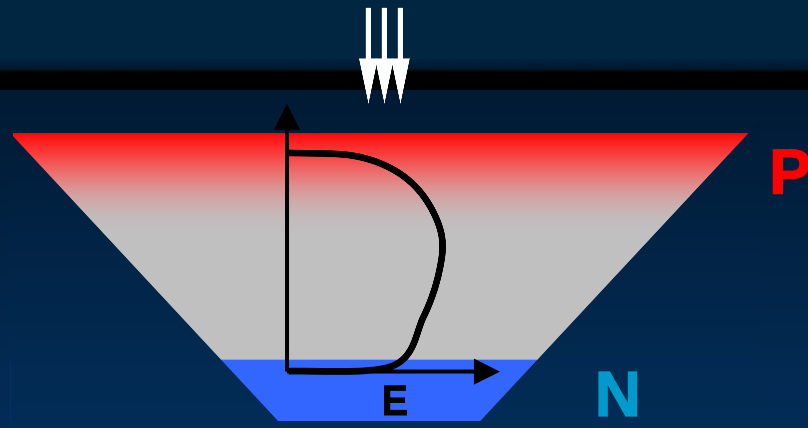
avalanching due to impact ionisation in high field region



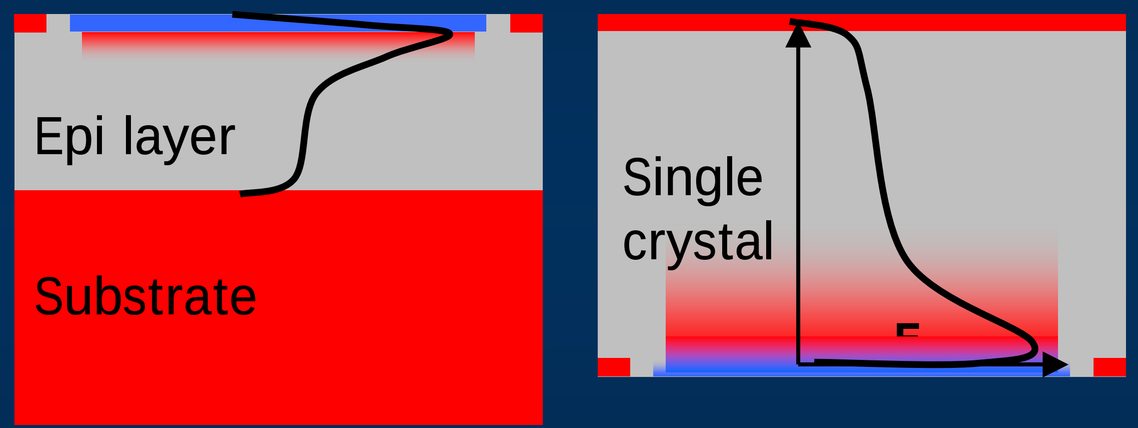
APD flavours

PerkinElmer™ optoelectronics.

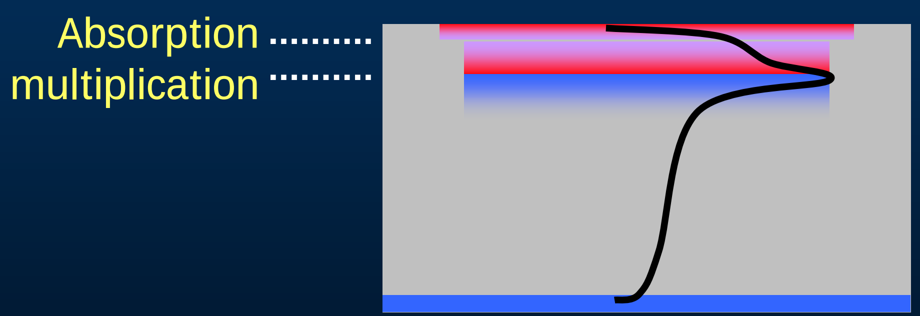
Bevelled edge



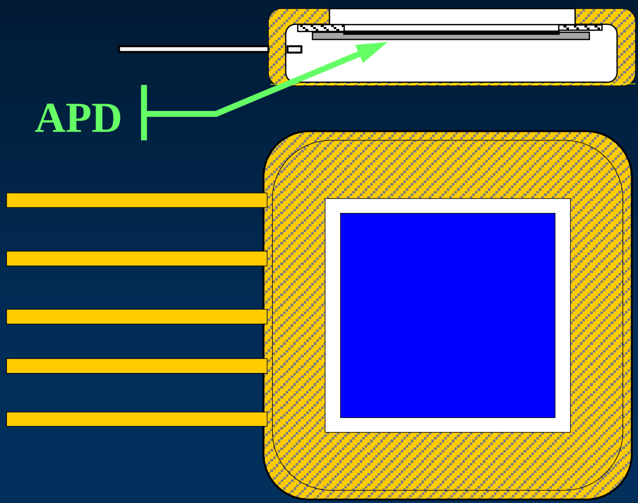
Reach-through



Buried Junction

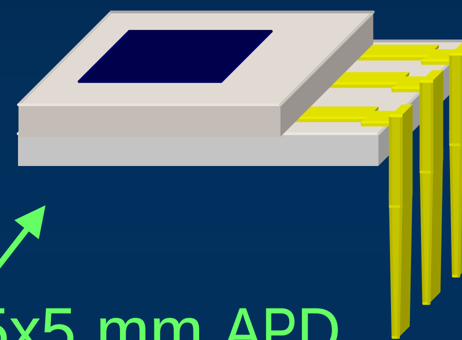


Very small occupied volume

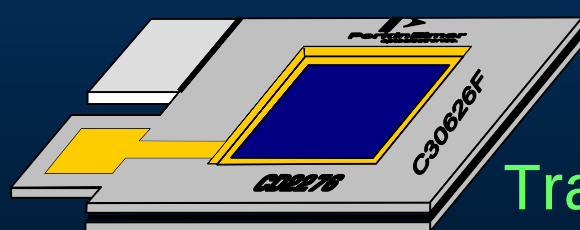


~2-3mm height

5x5, 10x10mm
active area



5x5 mm APD
package thickness ~1mm



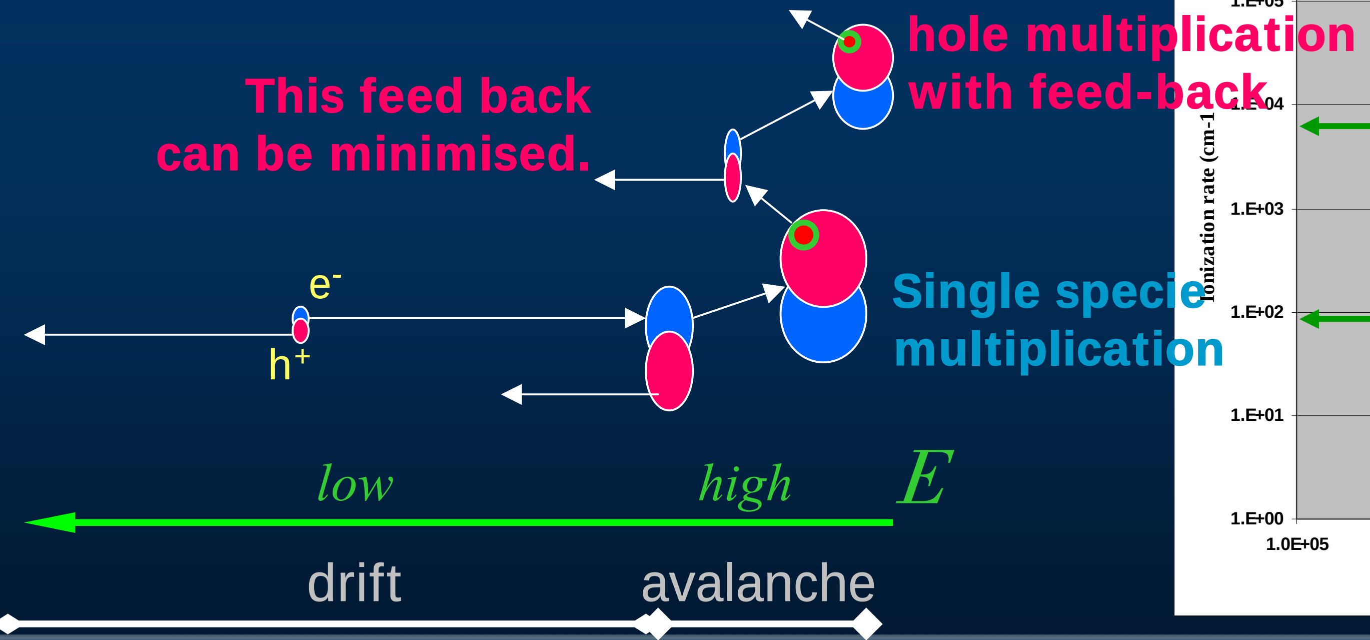
Transmission assembly

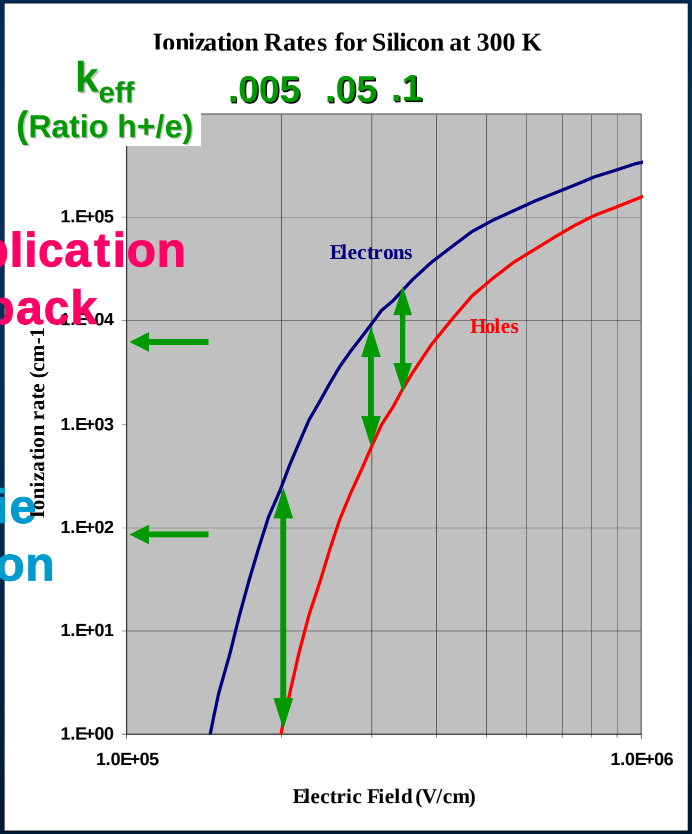
Gain (basic mechanism).

Gain is due to hot electrons impact ionisation.
Unfortunately, both holes and electrons can ionise .

The result is that while most of the electrons will undergo a simple multiplication. Once in a while a hole will generate another e-/h pair triggering a new avalanche.

This feed-back broadens the gain distribution and thus introduce extra noise.





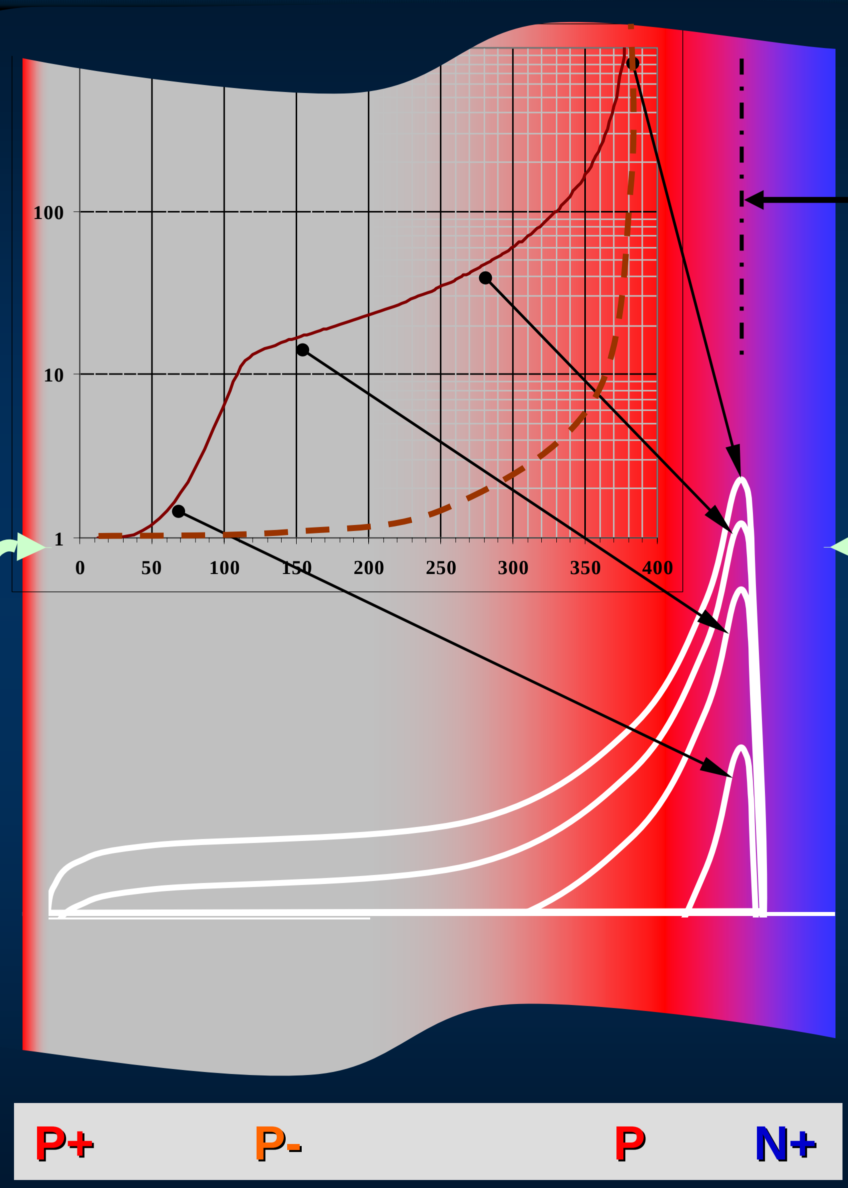
APD Gain Curve

$$\overline{M} = \frac{\overline{Ne}_{out}}{\overline{Ne}_{primaries}}$$

Gain vs. Bias

Different field profiles have different gain curves.

Rear entry



Junction

Front entry

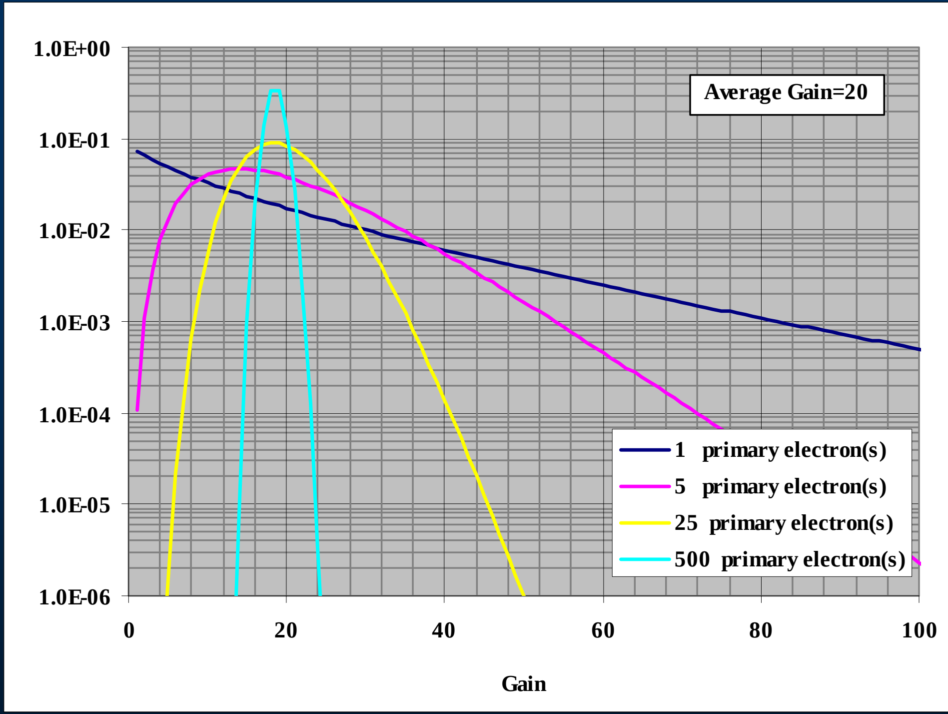
Schematic of the electrical field at various points along the gain curve

The Gain distribution

$$P_{n,n+r} = C(n,r,k) \otimes e^{-(n+r\times k)\delta} \frac{\left(1-e^{-(1-k)\delta}\right)^r}{(1-k)^r r!} \qquad \delta = \int_0^w \alpha \times dx$$

$$P_{n,n+r} = \frac{n}{\left[2\pi(n+r)\times((n+k\times r)r\right]^{.5}} \left(1-\frac{n\times X}{r}\right)^r \left(1+\frac{n(1-k)X}{n+k\times r}\right)^{\frac{(n+k\times r)}{(1-k)}}$$

$$X = (n+r-n\times M)/n\times M$$



Gain is a statistical distribution.

The width of the distribution can be characterised by the excess noise factor:

$$F = \frac{\overline{M^2}}{\overline{M}^2} = k_{eff} \times M + (1-k) \times \left(2 - \frac{1}{M}\right)$$

Noise (divers formulations depending on pre-amplifier)!!

PerkinElmer™ optoelectronics.

Other sources

Multiplication

$$\frac{\Delta E}{E} = 2.35\sqrt{\left(\frac{ENC}{M \times N}\right)^2 + \frac{(F-1)}{N} + \frac{\sigma_d^2}{N^2}}$$

ENC= equivalent noise charge

M = gain

N = number of primary electrons

$\tau = RC$

$\tau_c = 1 / 2\pi f_c$ *(corner frequency)*

$$ENC = \frac{1}{q}\sqrt{a_p i_n^2 \tau + a_s \frac{e_n^2 C_t^2}{\tau} + a_f \frac{e_n^2 C_t^2}{\tau_c}}$$

Divided by Gain

series noise

parallel noise

$$i_n^2 = 2q\left(i_s + i_d M^2 F\right)$$

Proportional to M^3/2

surface leakage current
NOT a source of noise

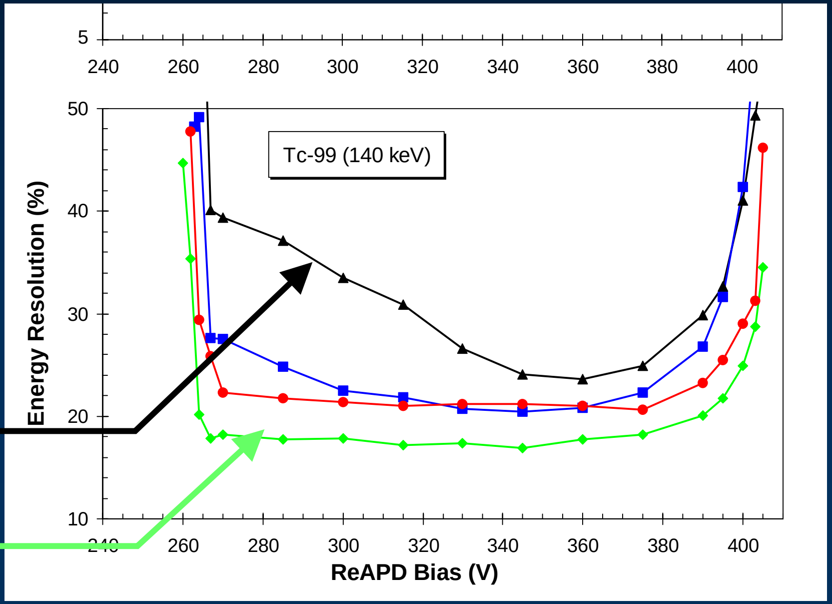
Bulk (multiplied)
leakage current

Energy resolution vs. Bias

Only with low electron yield does bias need to be increased.

~200 e$^-$

~1000 e$^-$



R. Lecomte et al. NIM-A 1999

Rule of thumbs M~ 30 to 70 sufficient.

If unusual conditions exist (e.g. noisy environment) higher gain up to 500-1000 usually possible.

Energy Resolution

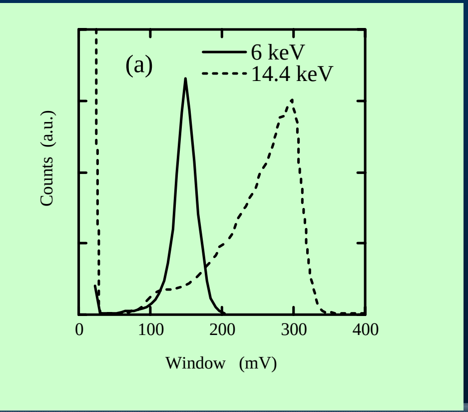
PerkinElmer™ optoelectronics.

- Noise (from previous slides)
  - Higher gain -> higher multiplication noise, lower electronics noise.
  - Optimum when both equal. moderate cooling 0-10°C may help.
  - Usually, best bias correspond to lowest gain that overcomes amplifier noise.

- Gain stability (PKI only:)
  - Bias : at M=30: δM ~0.5%/V; at M=100: δM~2%/V
  - Temperature: equivalent to ~0.5-2.5V/°C (3V/°C – 200µm thick)
  - If temperature unstable control bias.

A. Baron et al

- Saturation Effects.
  - local depletion of voltage
    strong signal, high gain, focused avalanche.
  - incomplete multiplication
    If interaction in avalanche region



Energy resolution

PerkinElmer™ optoelectronics.

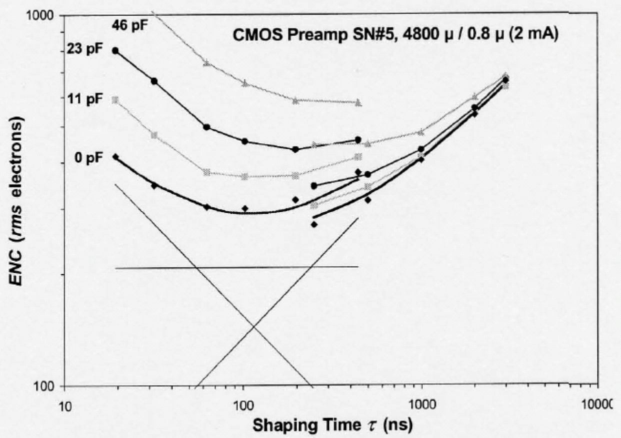


Figure 3 – Measured *ENC vs τ*, for various detector capacitance C_d. The discontinuity in the curves for a given detector capacitance results from the use of different filters for the short and long shaping times (see text). The straight lines represent the contributions from parallel, series and flicker noise to the fitted experimental data for an CR-RC shaper and C_d=0 pF.

Optimum resolution depends on amplifier characteristics, for energy measurements, usually 50 to 100 ns best

R. Lecomte et al

Gain saturation

Moszyński et al, NIM-A 2002

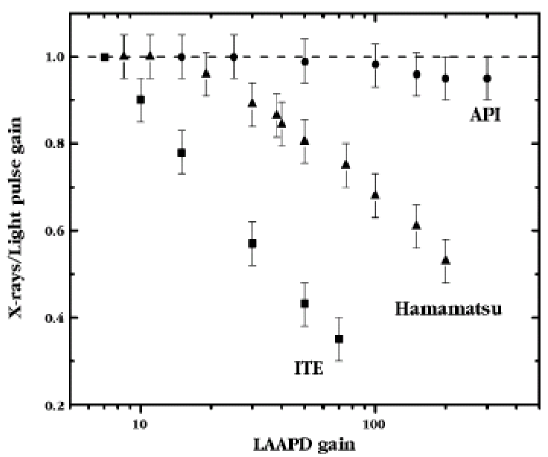


Fig. 7. Ratio of the LAAPD gain for 5.9 keV X-rays and light pulses vs. its gain as compared to the similar characteristics measured for Hamamatsu and ITE [33] APDs, as per [25].

Time resolution (signal shape)

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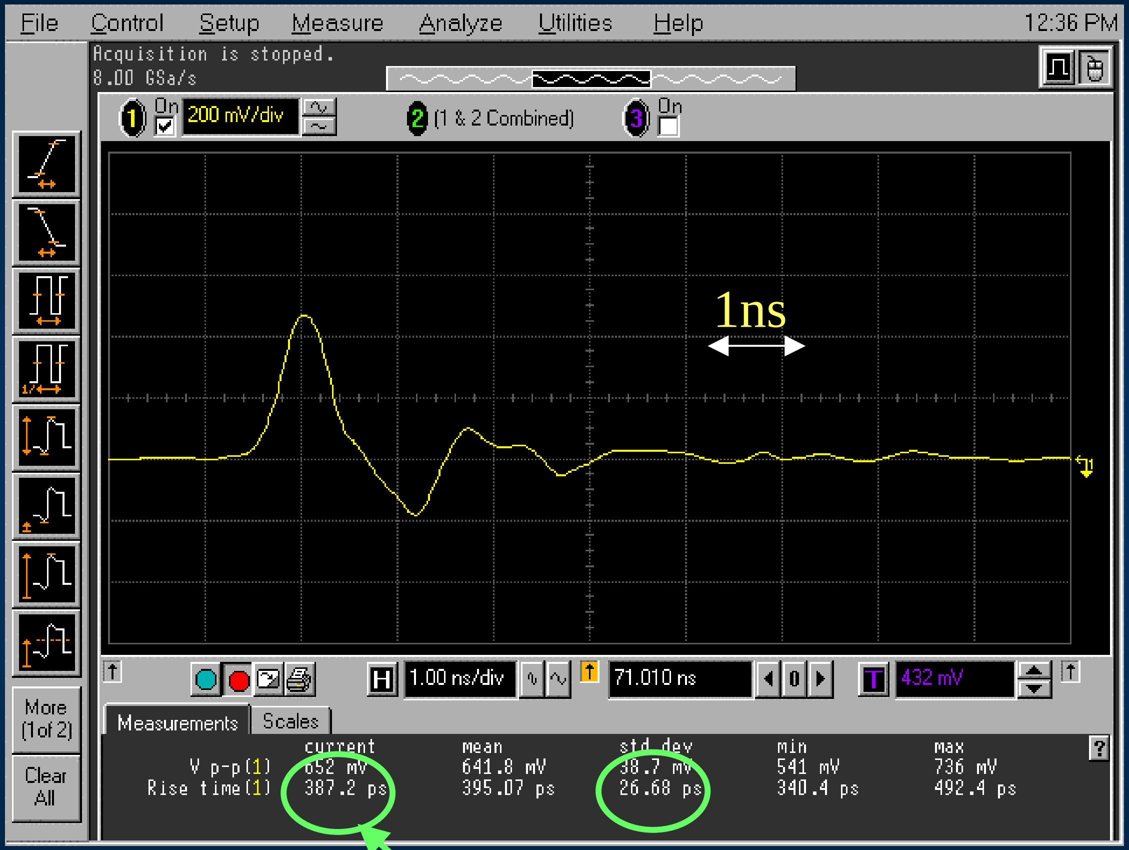
Electronics contribution.

$$\delta t_{Fwhm} = 2.35\sqrt{\left(\frac{\sigma_{\upsilon}}{\left(d\upsilon/dt\right)}\right)^2 + !!^2}$$

Signal from APD into 50 ohms. Coaxial cable, no particular precautions.

Laser excitation ~120ps wide.

Timing resolution of the order of 20 to 30ps have been measured using laser excitation.



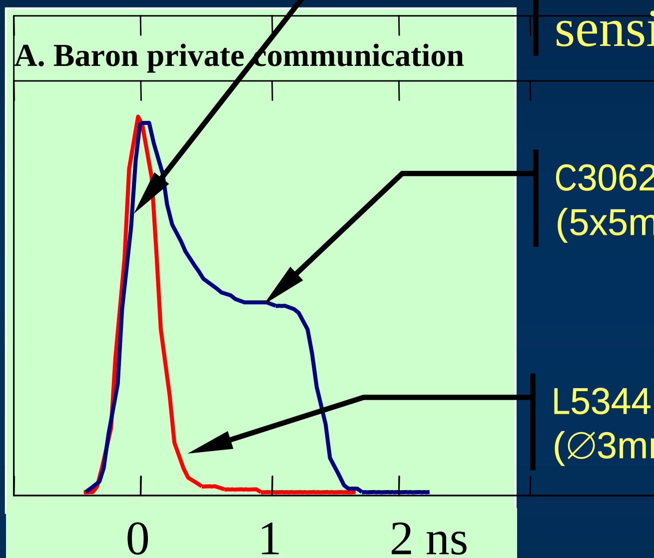
Pulse rise time ~400 ± 27 ps

Timing Resolution (APD thickness)

PerkinElmer™ optoelectronics.

- APD special effect.

Rise time not very sensitive to thickness.

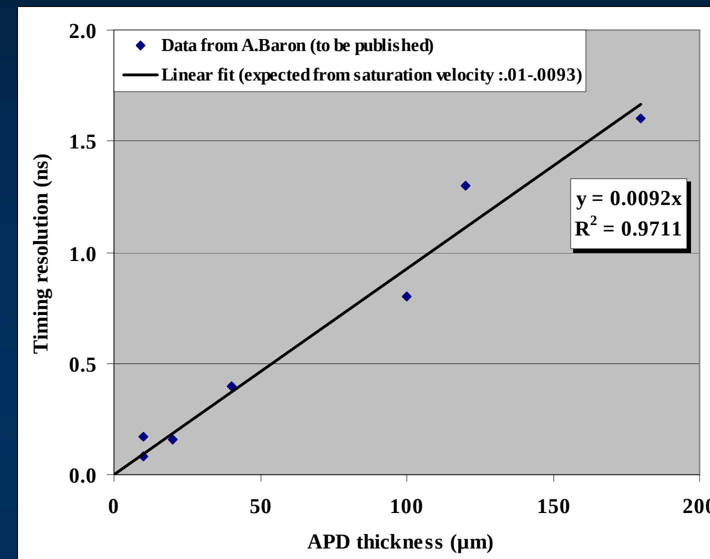


C30626
(5x5mm, ~100µm, ~30pF)

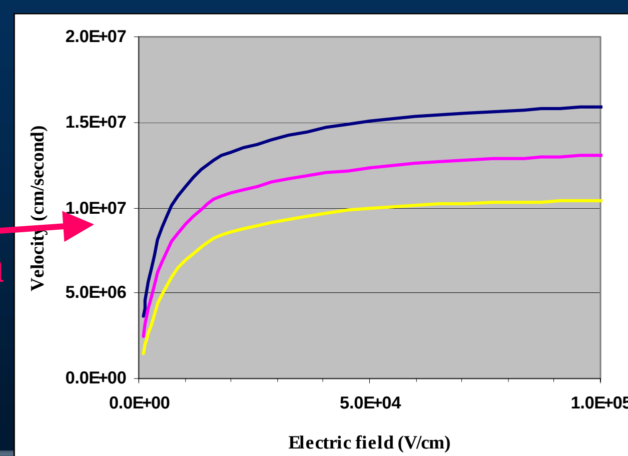
L5344
(∅3mm, ~20µm, ~30pF)

Transit time of e- through drift region of C30626

Timing resolution vs. APD thickness



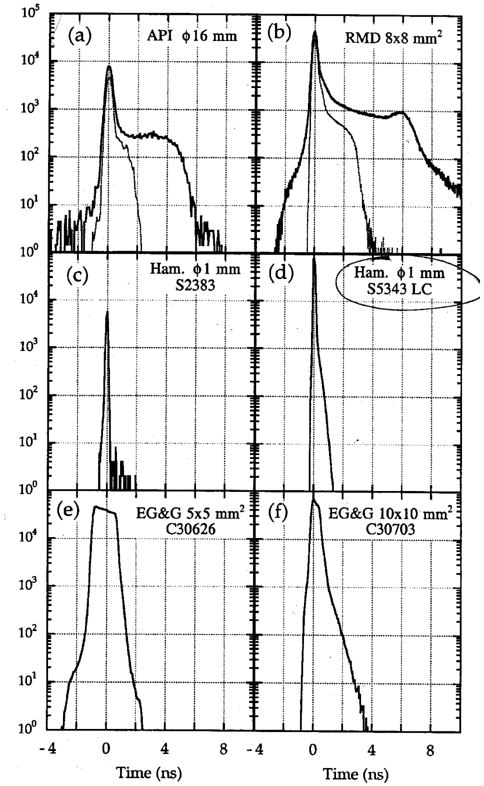
Velocity saturation



T (°C)
-50
0.
+20

Timing resolution

PerkinElmer™ optoelectronics.



Time response of various APD types., measured with X-rays from 14-16keV.

The tails in figures a) and b) are reduced by raising the energy discriminator theshold.

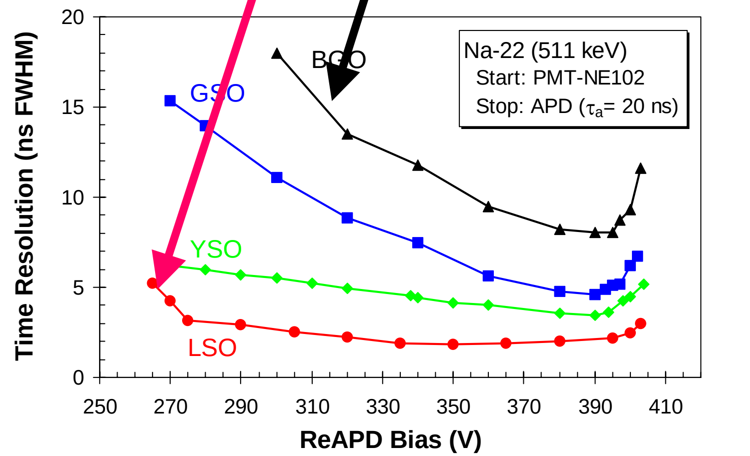
Note >4 order log scale

After AQR Baron, Hyperfine Interactions **125**(2000) 29-42

Note:
For most APD types, the tail is down by 4 orders of magnitude in a few ns.

3500 e^-

500 e^-



For thin APDs where transit time is not important, if there is a large number of electrons in the pulse then the bias does not matter, otherwise, bias close to Vb is best.
R. Lecomte et al (NIM-A 1999),

EVEN thick APD are very fast detectors.

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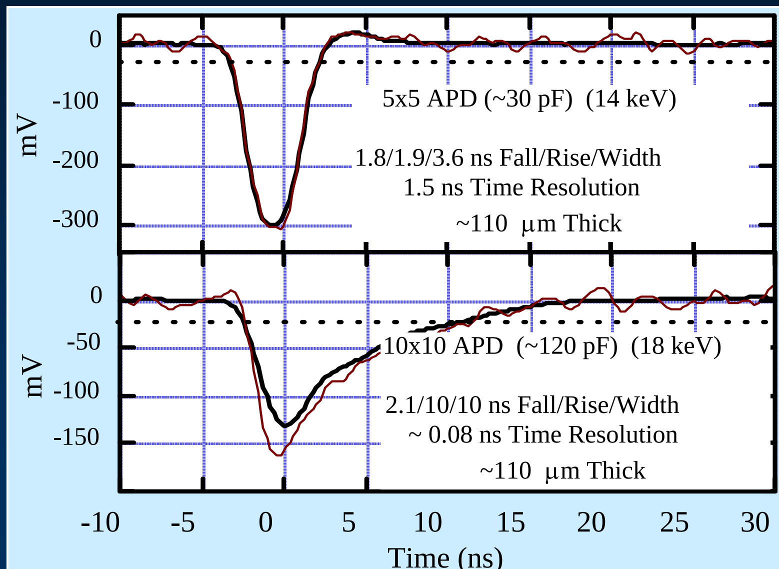
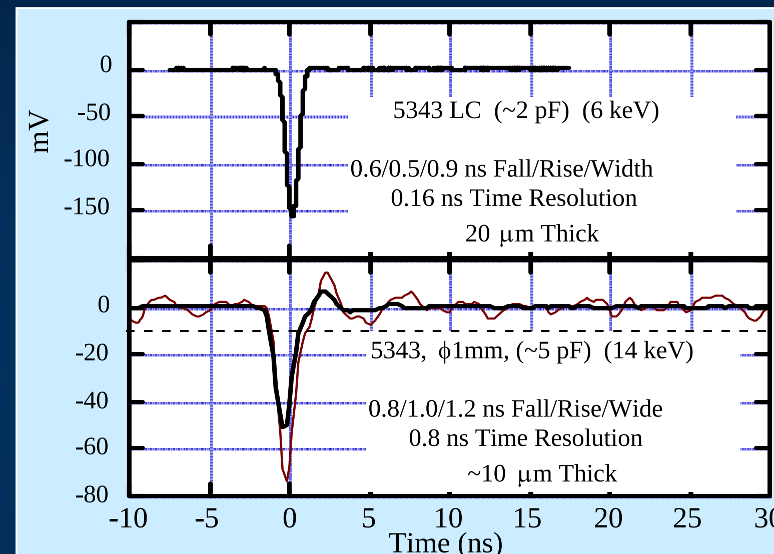
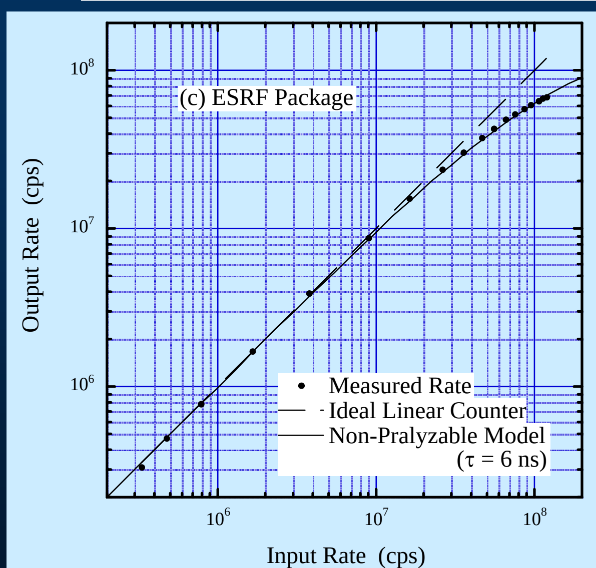


Alfred Baron et Al
(to be published)





Counting rate close to 10^{8} cps.
Extracted dead time 6ns

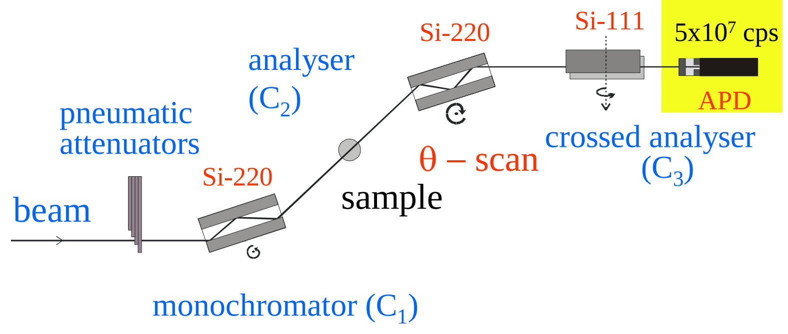
Results obtained with ESRF module developed by J-M Rigal and J. Morse

APD are FAST (data from ESRF)

PerkinElmer™ optoelectronics.

Ultra Small angle X-ray scattering: structure, dynamics, and phase behaviour of colloidal systems

Bonse-Hart Camera- APD detector setup at ID2

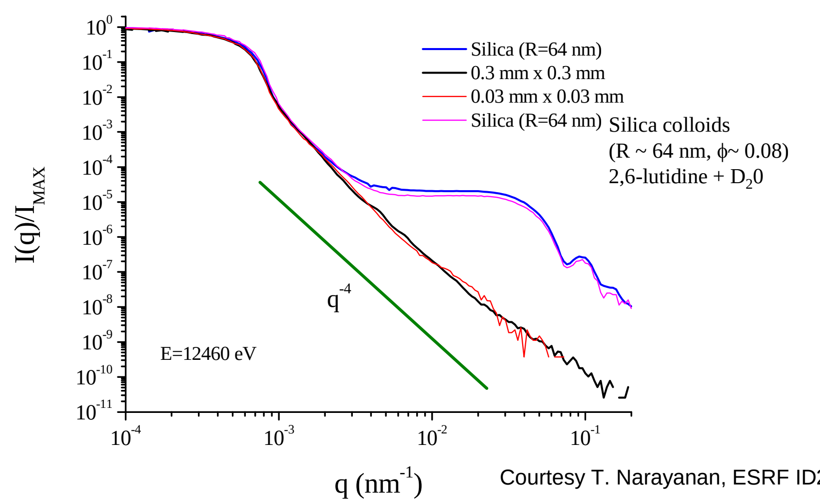


beam divergence: 35 mrad x 20 mrad

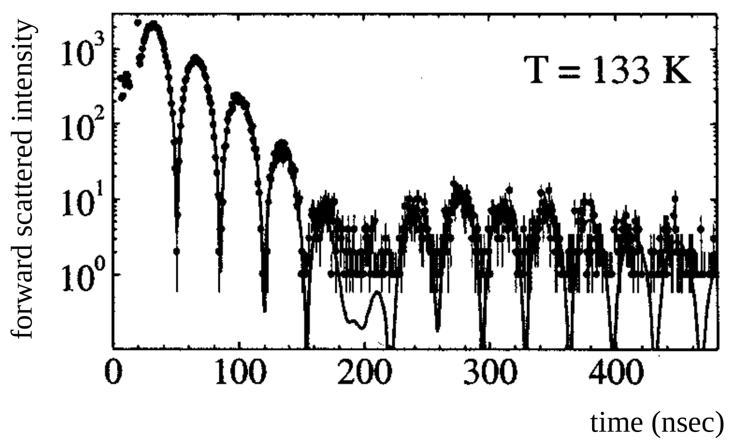
Courtesy T. Narayanan, ESRF ID2

Rocking curve with a partially coherent beam

Note signal dynamic *>10 orders of magnitude*



Courtesy T. Narayanan, ESRF ID2

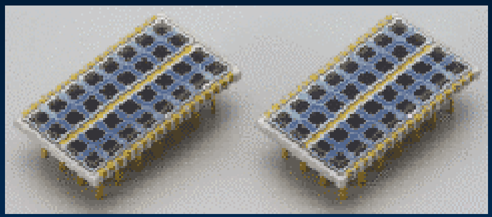


Quantum beats in nuclear forward scattering (14.4keV X rays) from ^{57}Fe nuclei, measured at ESRF-ID18 with an APD. Prompt recovery of the APD from X-ray signal saturation occuring at t=0 is essential.

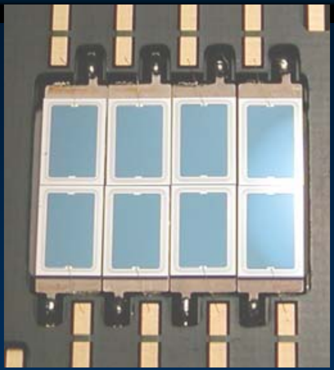
After H Paulsen, Eur. Phys. J. 23(2001)463-472)

Arrays
(not very common, but it is a question of demand)

PerkinElmer™ optoelectronics.

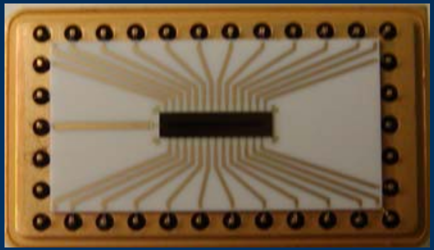


Semi integrated array
Pixel size ~2x2mm

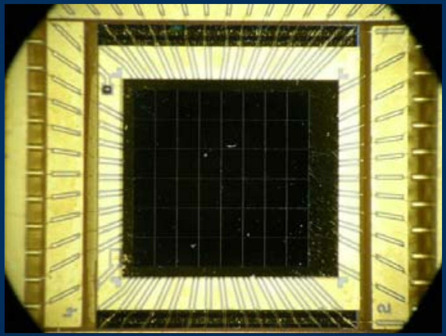


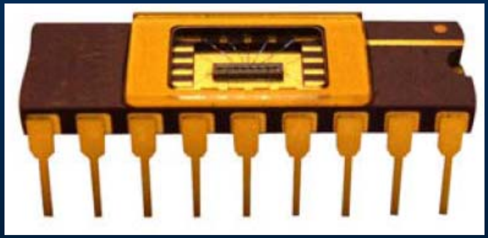
Discrete elements
Pixel size ~3x5mm

20 elements array
pixel size:250x400µm



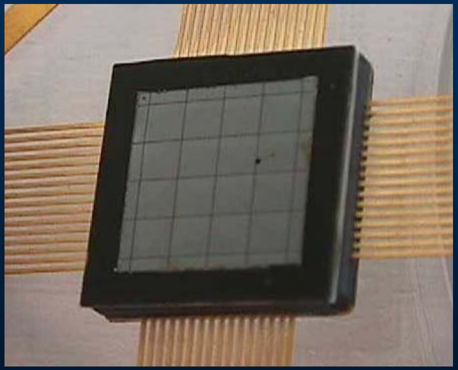
6x8elements
pixel size:1x1.3mm2





16 elements
pixel size ~200x650µm

4x4 array
pixel size ~ 2x2mm



Summary: APD status

PerkinElmer™ optoelectronics.

- APDs are small, very fast, solid-state devices
  Output signal exhibits ~30 ps to ns rise-time.
  Counting rate up to 10E8 is feasible.
  No residual signal (4 order of magnitude) after a few ns.
  10 order of magnitude in counting rate demonstrated.

- Pico to sub-nano second timing resolution ,with 10-20 % energy resolution is feasible.

- APDs are insensitive to magnetic fields.

- Low efficiency for X-ray energies > 20keV

- Carrier drift time can degrade timing resolution.

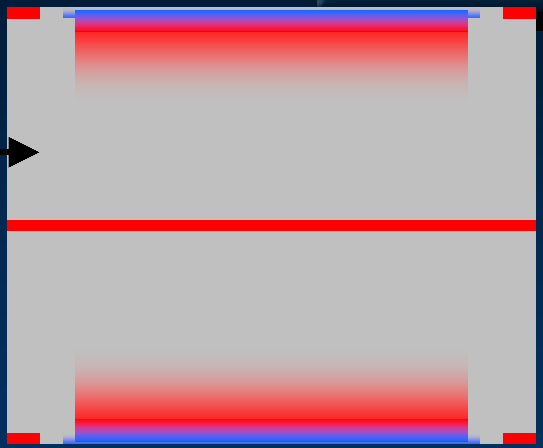
- Still further developments are possible.

Potential developments (Efficiency)

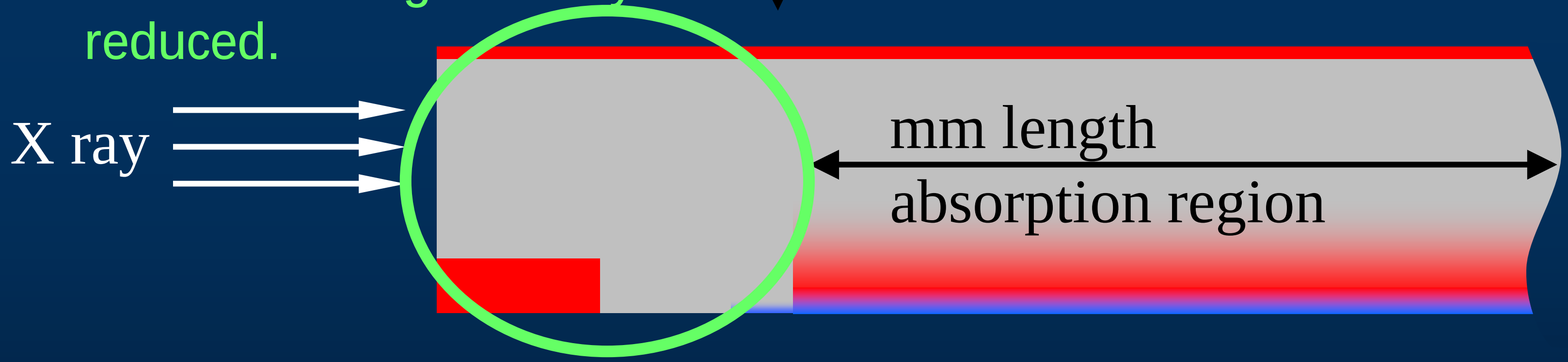
PerkinElmer™ optoelectronics.

➤Efficiency at high energy:

- **Multi stacks (at least 2 without dead layer).**
- **Edge entry devices,**
- **APD-scintillator assembly.**



Dead layer at the edge, needs to be significantly reduced.



➤Efficiency at low energy:

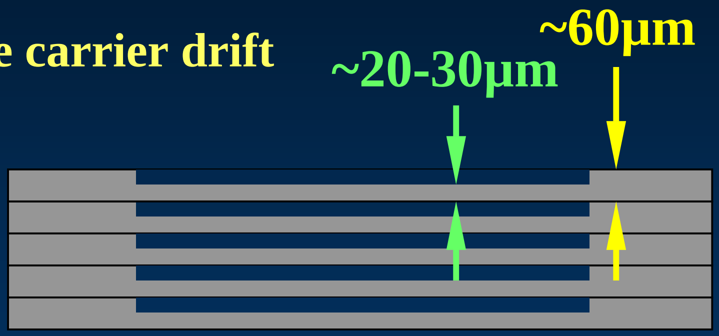
- **Geiger mode ?** ***(scintillating fibres, coupled to optical photon counting APD array)***
- **Thinner dead layer** ***(may require slight cooling)***

Potential developments (Timing, imaging)

PerkinElmer™ optoelectronics.

➤Timing:

- **Edge entry using a thin X-ray beam to remove carrier drift variability** ***(requires an improved edge dead layer.)***
- ***Stack of thin APDs***



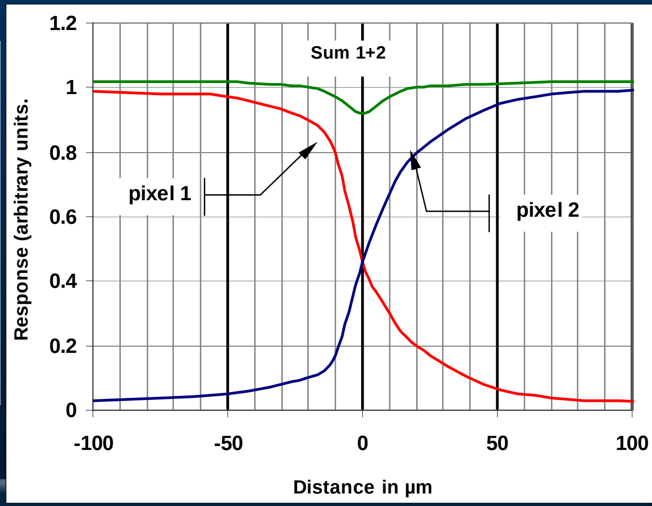
- **Cooling ~ -50 °C to -100°C ,** ***(below LN2 charges freeze out would be a potential issue).***

➤Imaging:

- NOT a technical issue. Almost any shape and size possible

•Limitations	Total active area	Minimum pixel size	Inter pixel dead space
Regular process	≲ 1cm^2	≳ 2 chip thickness	~2 chip thickness
Alternate process (used for C30927E)	"	≳ 10-20µm ?	No dead space, width of cross-over region limited by inter-electrode resistance.

Optical scan across 2 elements C30927E).



Conclusion

Let us know what you need
want
wish