Avalanche Diodes (APD) Detectors:
Introduction and Recent Advances*

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International Symposium on the Development of Detectors
for Particle, Astro-Particle, and Synchrotron Radiation Experiments
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*Focus on Fast X-Ray Detection

A Change in Scale…

Compared to the detector effort in high-energy physics, the effort in synchrotron radiation is in its childhood,

… and the APD effort in x-ray scattering is nearly a newborn.

Small efforts: ESRF, BNL, DESY, SPring-8, KEK, (SSRL)
& the recent addition of a dedicated technician
at ESRF is already a major jump.

Historical

Development in the 60s & 70s

(Huth, McIntyre, Webb, Jones at GE & RCA)

Some discussion of a "Solid State Photomultiplier"

(but gain not so high…)

Main utility is high speed (large gain-bandwidth product).

Optical Communication, Laser range-finding…

& Applications where for some reason a PMT is not suitable

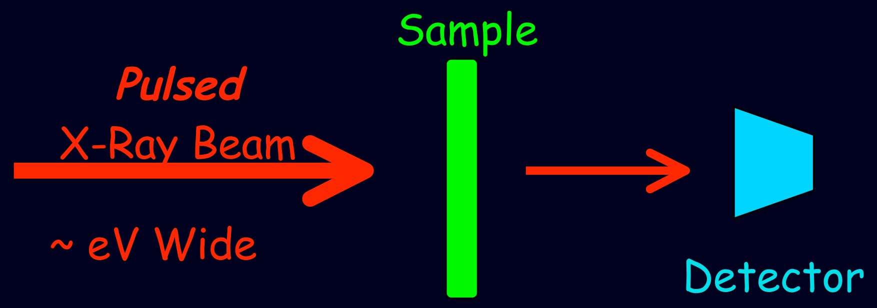
Positron Emission Tomography (High Magnetic Field)

Introduced to the x-ray scattering community via

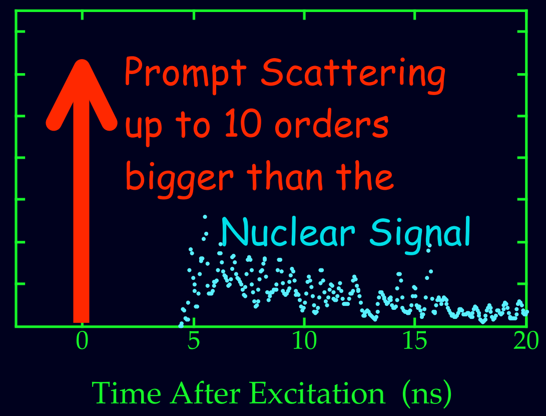
Nuclear Resonant Scattering (NRS) of Synchrotron Radiation

1990's

Nuclear Resonant Scattering (NRS)



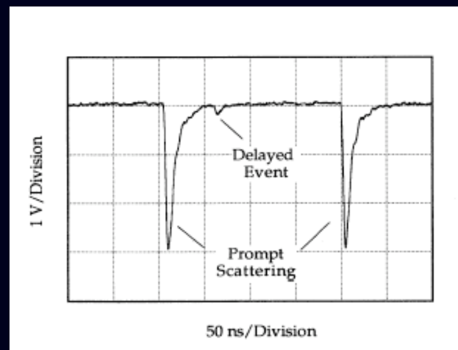
Resonant Nuclei
ΔE~ neV, τ~100 ns



Carefully Choose the Sample (Gerdau, Rüffer)

Build the Right Optics (Faigel, Siddons, Hastings)

Use the Right Detector (Kishimoto, Baron)



(1995)

Continues to provide a challenge for detectors...

APD Research Applications

Fast photon counting: 1 MHz Easy, ~100 MHz Possible

Diffraction, Imaging

Time resolved detection: ~1 ns Easy ~0.1 ns Possible

NRS, XIFS

Places where a PMT is not possible…

Magnetic Fields

Size Constraints

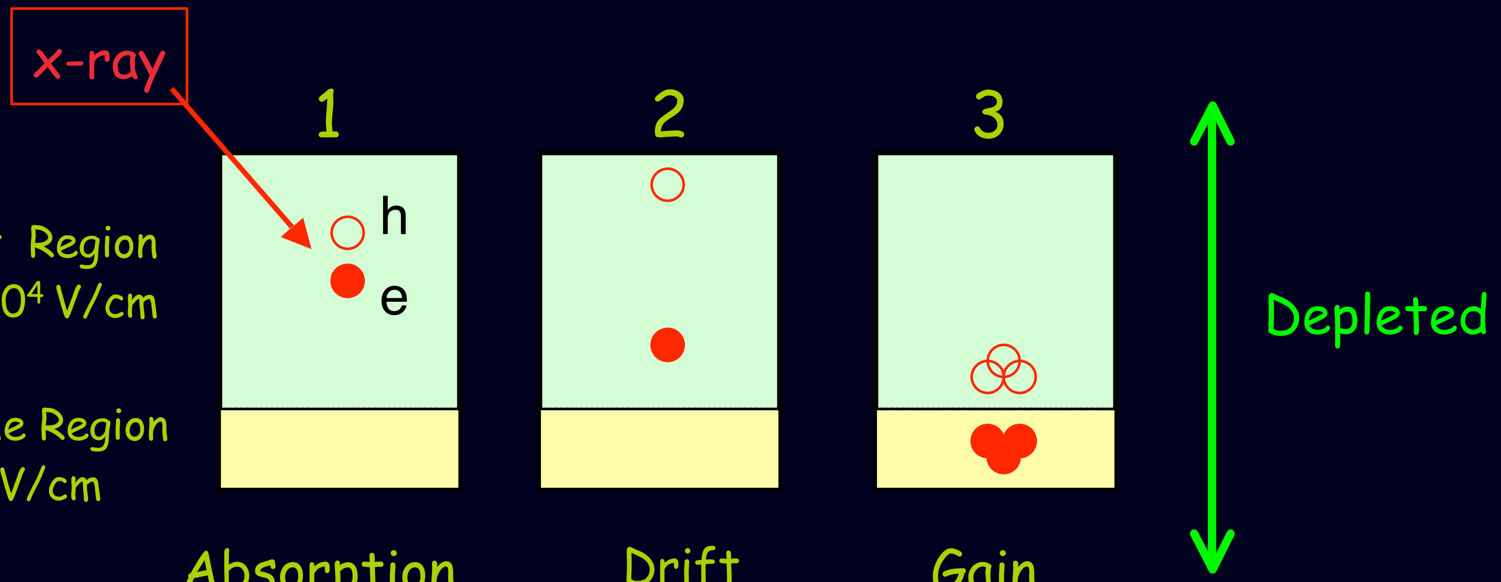
Power Requirements

Note one large application (>10^5 devices) is for the CMS Calorimeter for scintillator readout in a 4T field (Dieters, Renker)

A Diode With Gain

Drift Region
10^2-10^4 V/cm

Avalanche Region
~10^5 V/cm



Absorption
10-200 um Si

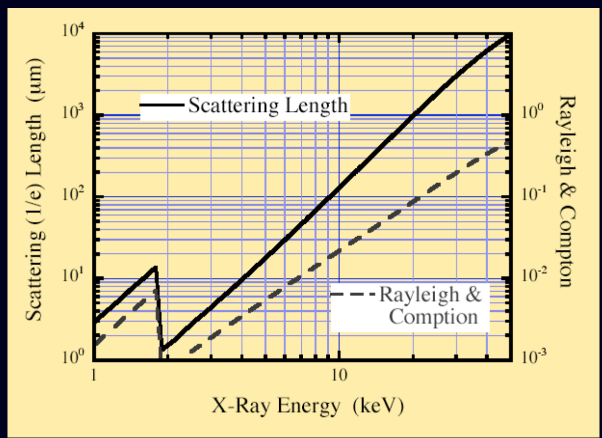
Drift
~ 10 ps/um

Gain
10^1-10^4

Limited Stopping Power

10 keV X-Rays -> OK

20 keV -> Losses



~50 Typical

Intrinsic (excess) noise due to amplification of BOTH Electrons & Holes

"McIntyre" Theory (~1970)

Geiger vs Linear Operation

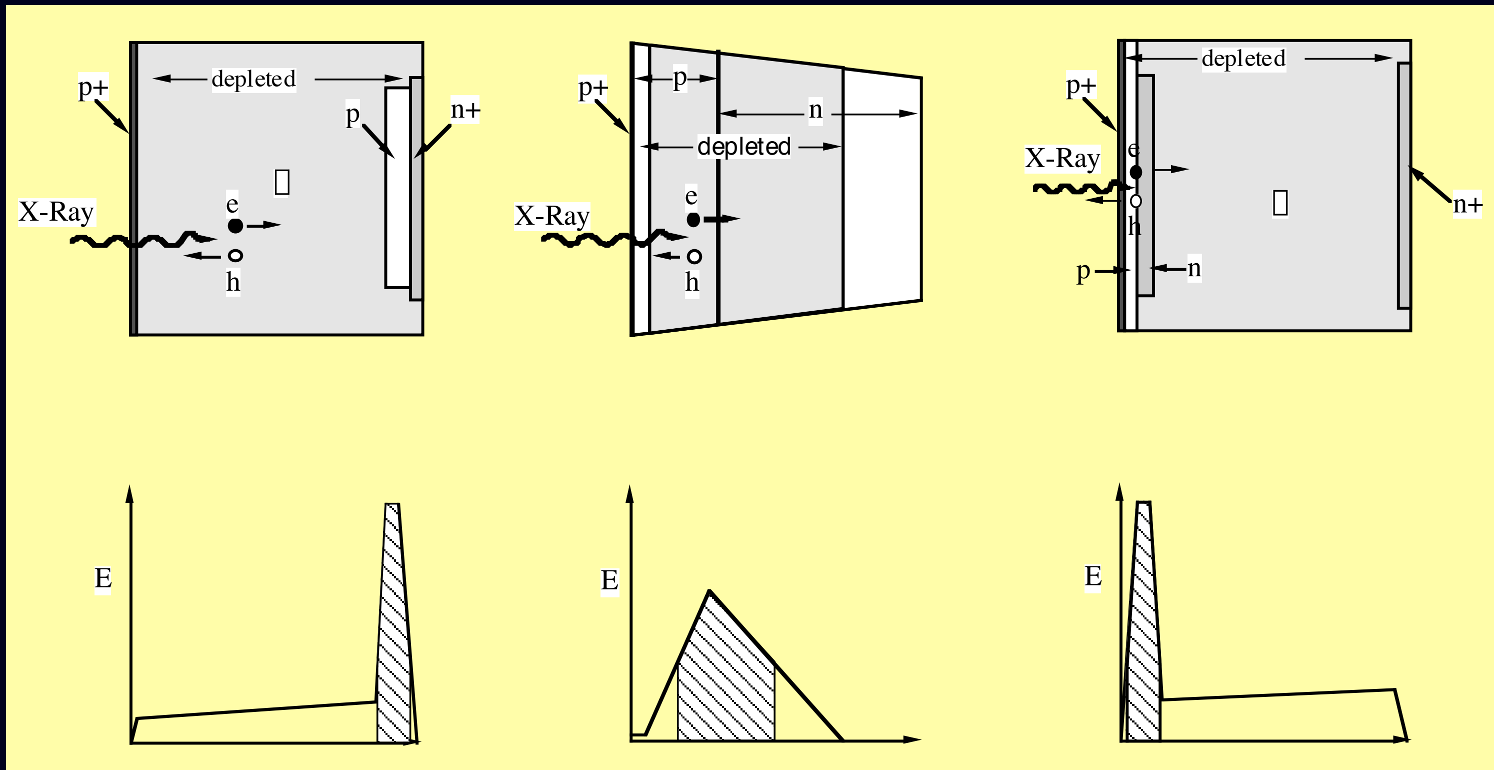
Linear Operation: Diode biased below breakdown.
Well defined small-signal gain.

Geiger Operation: Diode biased above breakdown.
Single electron leads to run-away gain until quenched.
Noisy: 10^2-10^5 cps/channel

(also Poster/Abs 143, Renker)

Structures

"Reach Through"	"Beveled Edge"	"Reverse"



"Reach Through"

Narrow Gain Region
Medium Voltage 50-700V
Large Drift Region
Modest Gains (<200)
Also one-sided epitaxial
& diffused & back entry…

"Beveled Edge"

Wide Gain Region
High Voltage (1-2 kV)
High Gains Possible
Larger Areas Possible
Also "Planar"

"Reverse"

Narrow Gain Region
Medium Voltage <500V
Small Drift Region
Modest Gains (<200)

Some Single-Element Devices

Company	Model	Size	Operating Voltage	Active Thickness (μm)	Capacitance pF/mm² (a)	Gain (a)	Time Resolution FWHM / Tail (ns)	
Perkin-Elmer (PKI /EG&G)	C30626	5x5 mm² & smaller	300-400	~110	1.2	50-150	~ 1 / 3	Reliable
	C30703	10x10 mm²	350-450	~110	1.2	50-150	~1 / 4	
	Prototype (b)	10x10 mm²:	350-450	~180	< 1	50-150	1.7 / 7	
	C30719 (b) Reverse	5x5 mm²	350-450	< 10	-	~50	0.17 / 2-3 (c)	
Hamamatsu	SPL2625 (b)	φ 3 mm 3x5 mm²	500-700	~ 130	~1	30-50	1.3 / 3	Mostly Reliable
	S238X	φ0.2 to 5 mm	~150	~ 30	6	50-100	0.3 / 5 (c)	
	S534X	φ1, 35 mm	~150	~ 10	16	~50	~0.08 / <2	
	S534X LC (b)	φ1, 3, 5 mm	~250	~ 20	5	~50	~0.15 / <2	
	S8644-XXK Reverse	φ0.2 to 5 mm & 5x5 mm² &10x10 mm²	~400	~ 7	3	~50	~0.25 / <2	
Advanced Photonix, Inc. (API)	LAAPD Beveled Edge	φ3 to 16 mm	~2000	30-50	~1	~200	~0.4 / >5 (c)	Not So Reliable*
Radiation Monitoring Devices (RMD)	S0814 S1315 Beveled Edge	8x8 mm² 13x13 mm²	~1700	30-50	~1?	300-2000	~0.4 / >10 (c)	Not So Reliable*

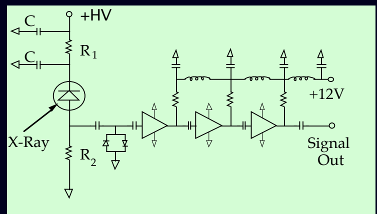
Note: (1) *Not* extremely careful conditions.
(2) Device Dependence.
(3) CMS expects >99% reliability (after selection) for 10 years

* As of ~1998

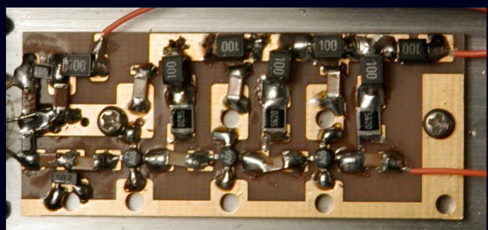
Electronics

- Photon (Pulse) Counting & Timing

APD → Fast Voltage Pre-Amp ~ GHz → Discriminator (NIM or ECL) → Logic → Counter Or TAC/TDC Or Autocorrelator



Not **YET** integrated… SM Technology & Modular (NIM) electronics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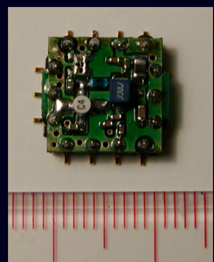
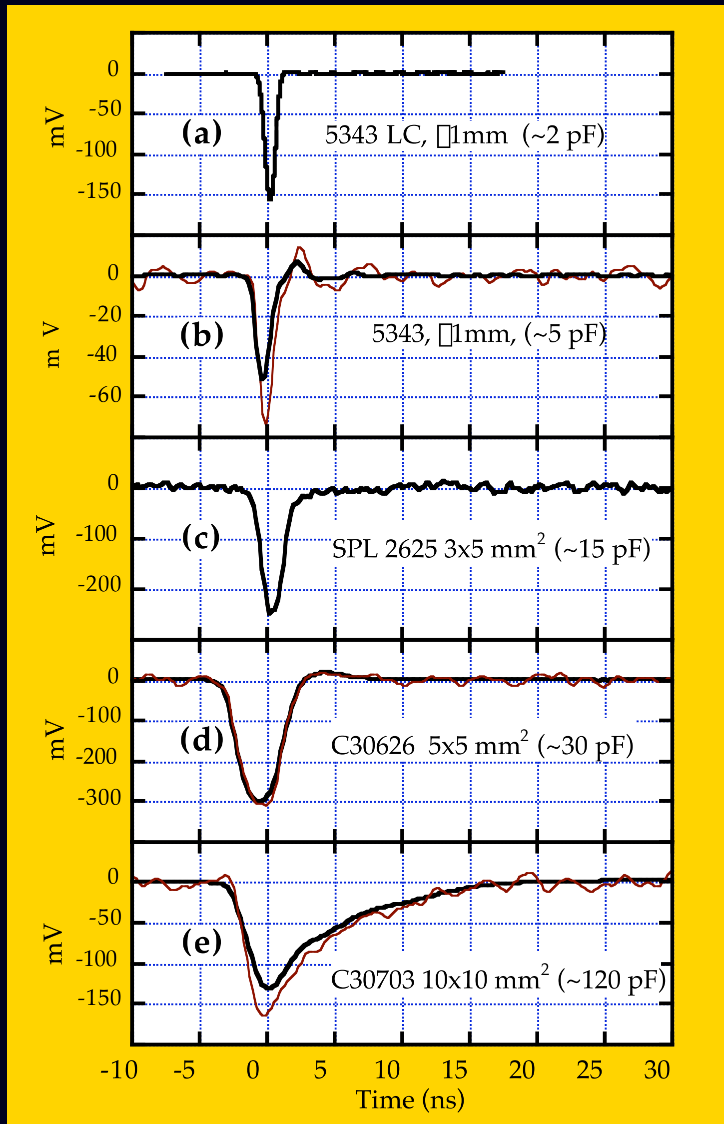

→ ASIC ?

Typical Scope Traces

Leading edge (rise time) is governed by carrier transport in the device

Trailing edge by diode capacitance and amplifier impedance

Best case ~ 0.6 to 0.9 ns FWHM



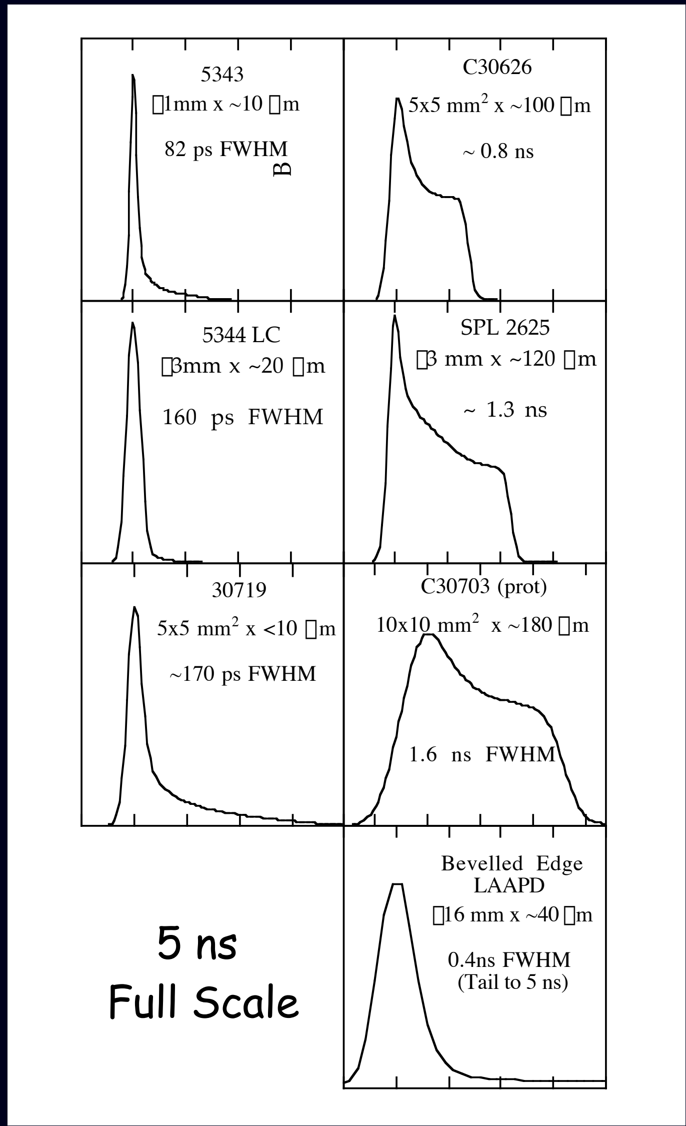
X-Ray Time Resolution

As x-rays penetrate and tend to uniformly illuminate a device, the FWHM of the time resolution is mostly determined by the thickness of the drift region

~ 10 ps/um near saturation

Tails determined by the field profiles near the surface

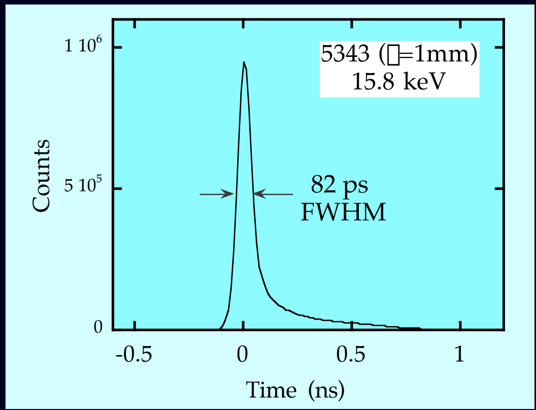
Note use of leading edge discriminator.

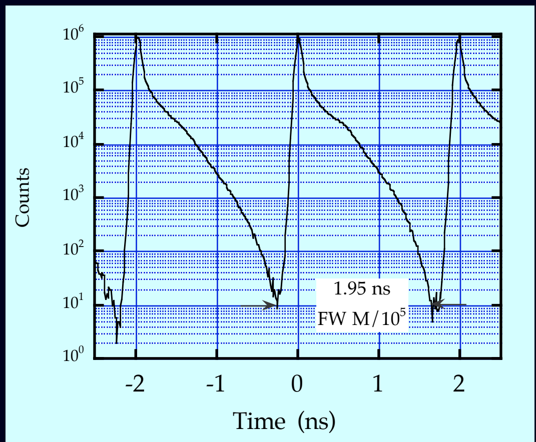


Best Time Resolution

Best FWHM: 75 ps

~ 10 um Device, Hamamatsu

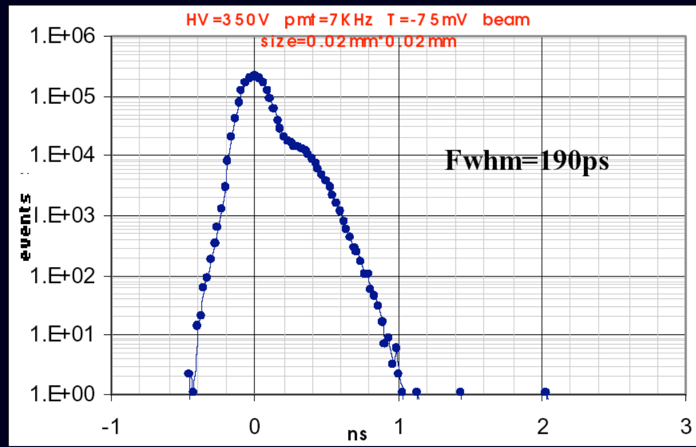




Good Tail: < 2 ns at $1/10^5$

Best Tail: ~1.4 ns at $1/10^5$

~30 um Device, PKI



(Work in progress, Deschaux, *et al*)

Note: Geiger Mode operation of small area devices has shown ~20 to 30 ps nominal resolution

(Cova, Lacaita)

Fast Counting

Simplest "Non-Paralyzable" Model

$$n = \frac{m}{1 - mT}$$

n = True Rate, m = Measured Rate

T = System Dead Time

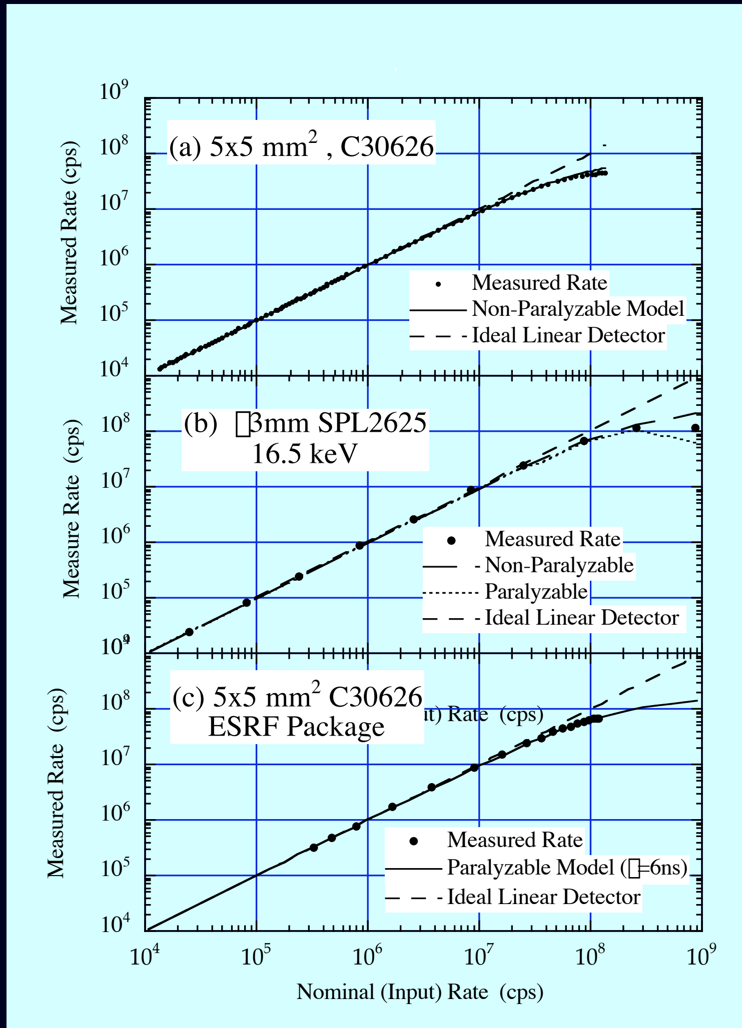
T = 3 to 20 ns

Source + APD + Discriminator + Counter

mT = 0.1 (20 MHz for T=5 ns)

-> Can correct to ~1%

For mT > 0.1 -> MUST Calibrate!



Pulse Height Distribution

(X-Rays and Fast Electronics)

Contributions:

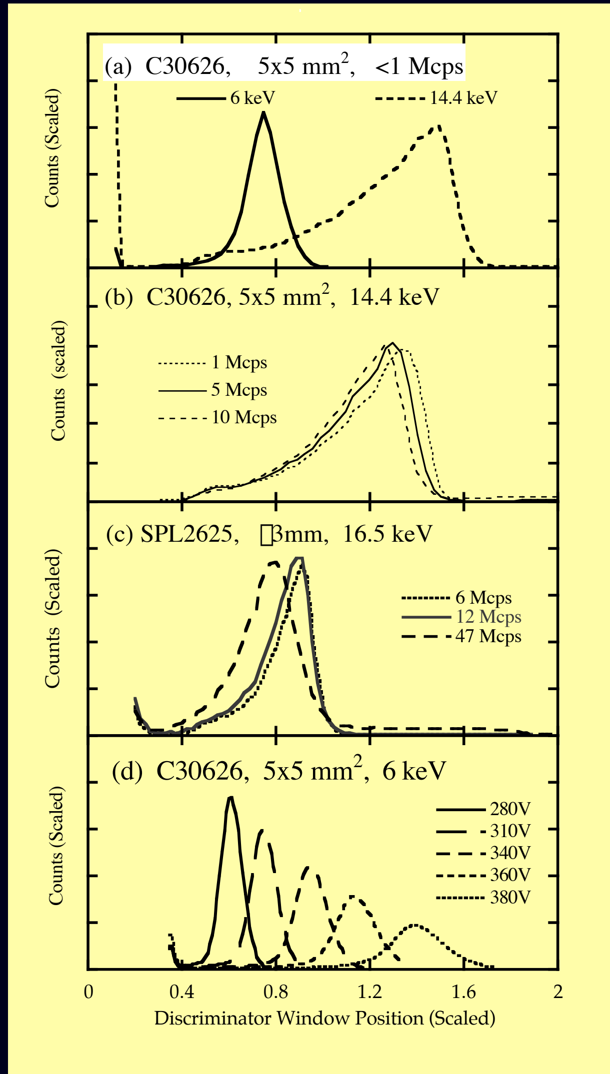
- Amplifier Noise
- APD Gain Noise
- Penetration into gain region

Typically 20-30% for thicker devices.

Base-line shift at high rates (AC-Coupling).
Better for lower capacitance devices.

Note: Slow Electronics, Low Gains, Cooling (-20C)
-> resolution ~5% possible

(Kishimoto)



Other Points

Low T operation is possible - increased gain and T-sensitivity

~ 40K with API Beveled Edge (Yang)

~ 100K with Ham. Rev. APD (Dorokhov)

Electron Detection is possible - note radiation damage!

Hamamatsu Devices with special surface (Kishimoto)

With Gain - VAPD (Kushman)

Progress toward a more realistic PMT replacement?

Many ($10^3/mm^2$) Geiger mode devices to keep

dynamic range & high gain (Buzhan, Sadygov)

(Next Talk, Otte and poster/ abs 126: Yokoyama)

APD Arrays

Company	Device Structure	Type	Array Pixels	Pixel Size	Dead Space (mm)	Reference
Perkin-Elmer (PKI /EG&G)	C30985 (a)	M	1 x 25	~0.4 mm x 0.3 mm pitch	~0.07	Webb & McIntyre, 1984
	(a)	M	1 x 32	0.35 mm x 0.15 mm pitch	~0.05	Trakalo, *et al.*, 1987
	(a)	M	1 x 128	2 mm x 0.15 mm pitch	~0.05	Webb & Dion, 1991
Hamamatsu	S238X	M	1 x 16	φ1 or 1 x 1 mm^2	0.1	Hara, *et al.*, 1996
	(b)	M	1 x 32	3.8 x 0.5 mm^2	Var.	Nonaka, *et al.*, 1996
	S534X LC	M	1 x 16	2.5 x 1 mm^2	0.1	Baron, *et al.*, 2004
	SPL2625	A	2 x16 & 2 x 4	3 x 5 mm^2	1	Kishimoto, *et al.*, 2004
	50 μm (c)	M	2 x 4	1 x 0.5 mm^2	0.1	Kishimoto, *et al.*, 2004
	S5343 LC	R	1 x 10	φ3	3 or 0.1	This work.
Advanced Photonix, Inc. (API)	Bev. Edge	M	8 x 8	1.3 x 1.3 mm^2	0	Gramsch, *et al.*, 1993
	Grooved			0.5 x 0.5 mm^2	0	Gramsch, *et al.*, 1994
Radiation Monitoring Devices (RMD)	Plan. Bev. Grooved	M	4 x 4	2.1 x 2.1 mm^2	0.4	Farrell, *et al.*, 2000
			8 x 8	13 x 13 mm^2	0.4	
	Plan. Bev Grooved.	M	14 x14	2 x 2 mm^2 Pitch	0.1	Shah, *et al.*, 2001
	Plan. Bev Anger. (d)	M	1 (d)	14 x 14 mm^2 (d)	0	Levine, *et al.*, 2004

M=Monolithic A=Assembled R=Replaceable

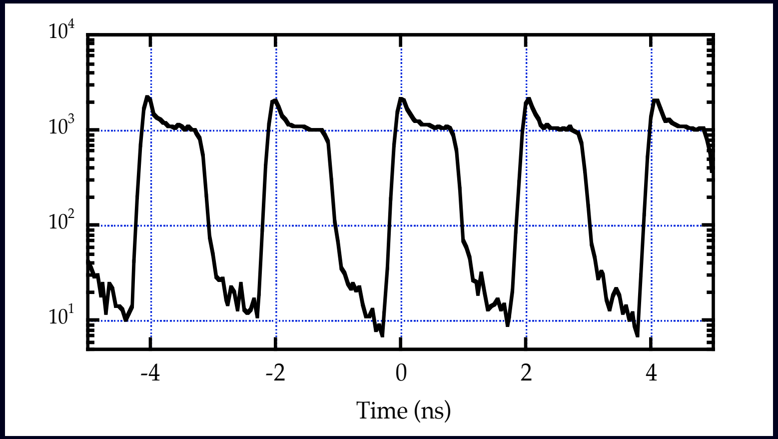
Note: Still relatively small numbers of pixels

ns Linear Array

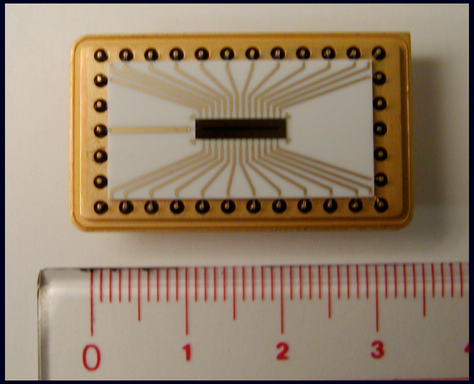
(Webb & McIntyre, 1984 - PKI C30985)

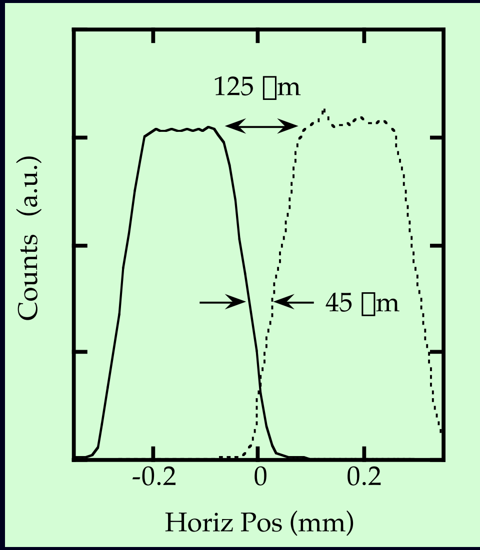
Linear Array, 25 elements, 0.3 mm pitch
~ 100 um thick, ~1 ns resolution

Segmented cathode with bump bonding.



~1 ns resolution



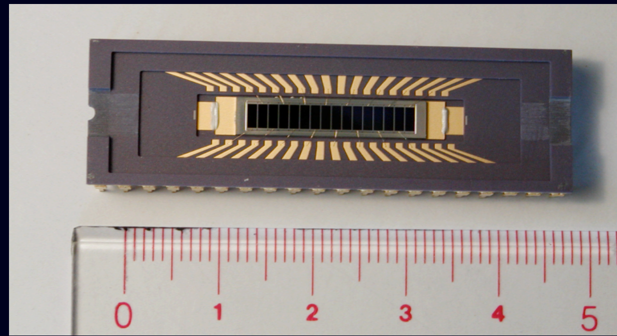


Fast Linear Array

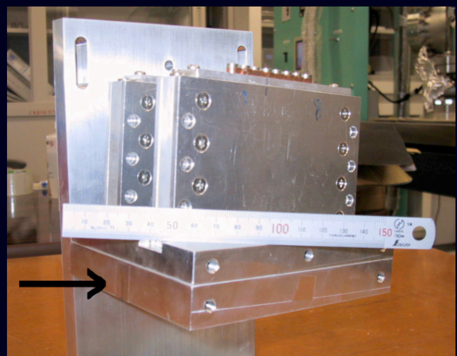
How can one keep good (200 ps) time resolution and high efficiency?

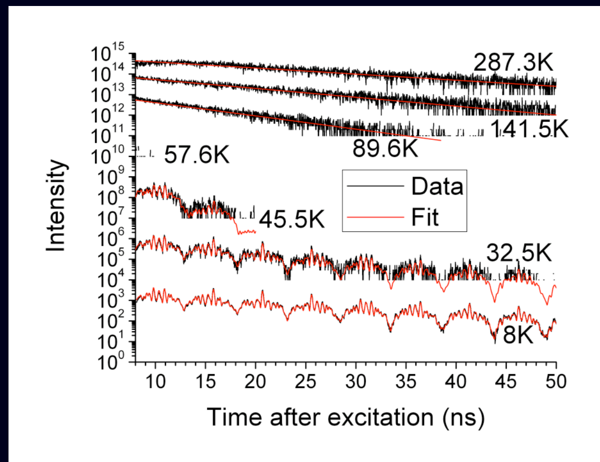
-> Grazing Incidence

16 Elements, 1.1 mm pitch
1x2.5 mm^2 x 20 um thick



2 Degree grazing angle -> 0.6 x 2.5 mm Acceptance, 0.6 mm Thick
Efficiency: ~1% -> 17 %





Magnetic Relaxation in Spin-Ice (Sutter et al)

Note: Device stability is an issue.

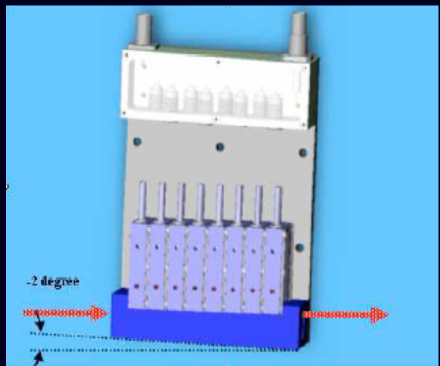
Modular Array

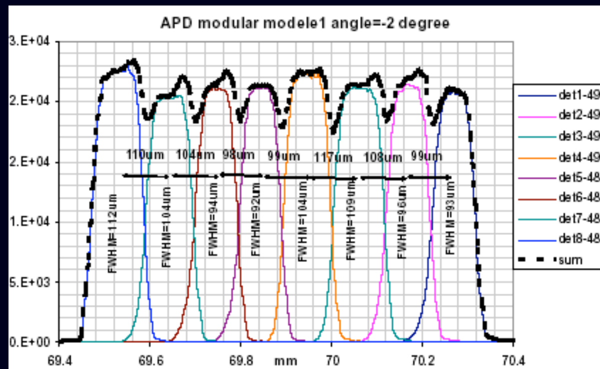
Now Under Construction - SPring-8 - ESRF Collaboration

Similar concept to the "Fast Array"

Grazing incidence gets you good (200 ps) time resolution and good x-ray stopping power

But Modular: Element replacement possible.
Amplifier design simplified.





8 Elements, 3mm x 20 um, incline at 2 degrees -> ~ 0.8 x 2.0 mm^2 x 0.6 mm thick

The Next Step: Integration

Discussion/Collaboration:

ESRF, APS, SPring-8, DESY, KEK, &..

First Goal (?): Fast (us) framing detector.

A Properly Instrumented APD Array

Pixel Size: ~ 0.3 x 0.3 mm^2 x 0.2 mm thick

(Efficient and ~ 2 ns time resolution)

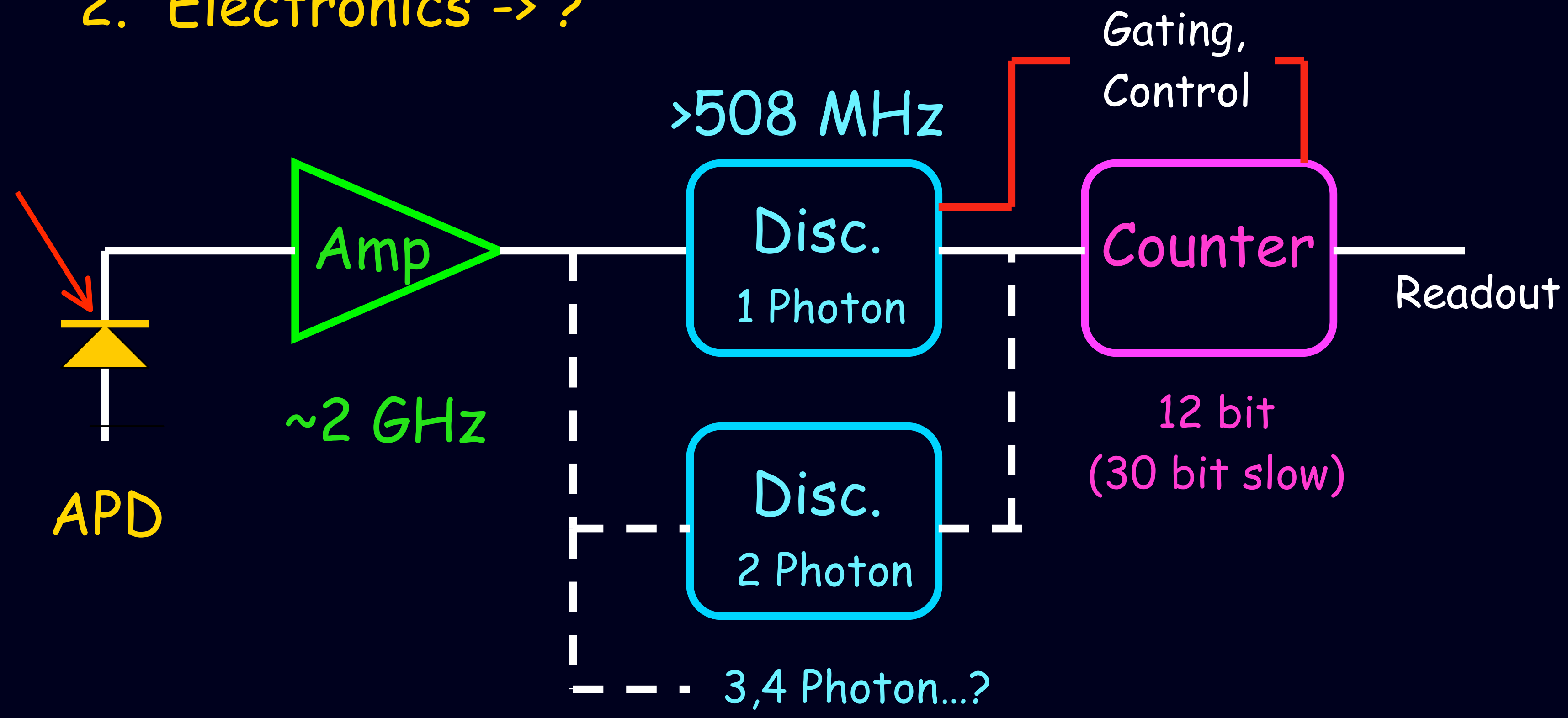
~10^3 channels (1 cm^2) at first -> 10^5

Utility: Fast imaging, Stroboscopic Measurements, XPCS

With different electronics, NRS: NSAXS, SRPAC

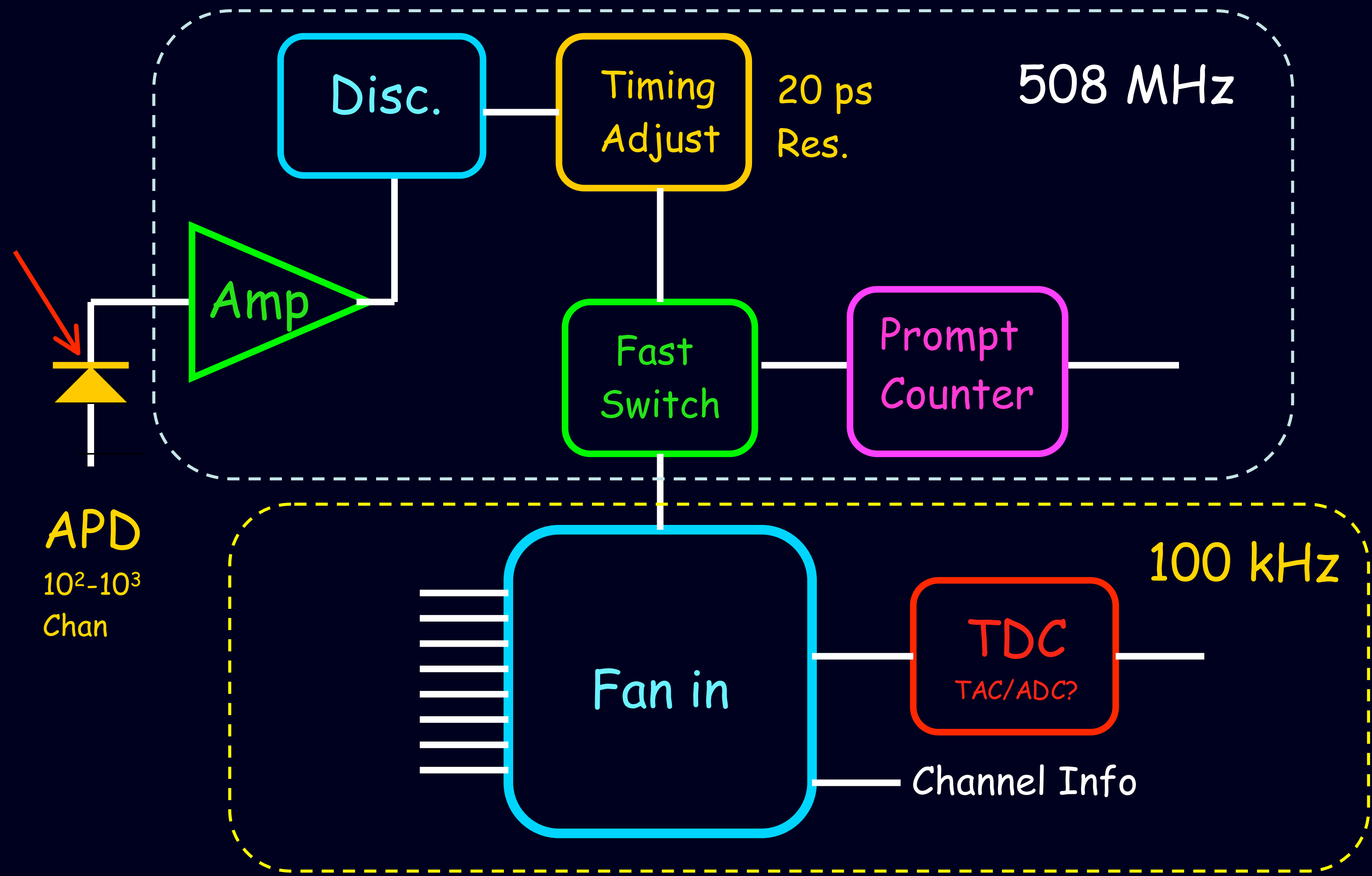
Fast Framing Detector

1. The Array Device -> Not so hard.
2. Electronics -> ?



Question: On board histogramming for stroboscopic work?

Modified Electronic for NRS



APD Collaborators

KEK: S. Kishimoto

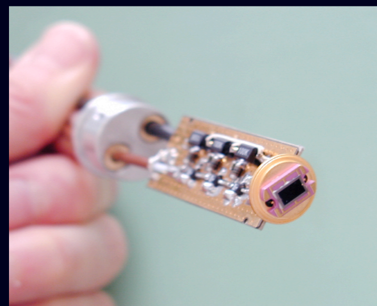
ESRF: T. Deschaux, R. Rüffer

SPring-8: T. Ishikawa (& T. Kudo)

Packaged Fast Counting Systems

BNL

Kuczewski, Siddons



ESRF

Rigal, Morse, et al.