Avalanche Photodiodes at ESRF

Instrument Support Group,
Experiments Division
**APD History:**

At ESRF, ~50 NaI, YAP -PMT scintillation counters for diffraction, scattering and beam monitoring applications.

These are limited to $<10^5 \ldots 10^6$ cps,

**WIDESPREAD DEMAND FOR A FASTER COUNTER**

Silicon APDs used since ~1993 (A. Baron et al.) for Mossbauer experiments with $<\text{nanosec}$ timing resolution

!! Could also be used as a fast counter ($>10^7$ cps), but devices difficult/impossible to use for non-specialist users:
- array of NIM modules,
- need for fast oscilloscope
- sensitive manual adjustments (HT bias, etc...)
"Reach-through" avalanche photodiode*

Extremely robust devices
Thin, high field, 'dead layer' p+ entrance
Available commercially (infrared ranging market)

number of electron-hole pairs for a 5.9keV photon is = 
\[ \frac{5900}{3.62} = 1630 \]

Charge collected in \(~1\text{ns}\), gives a current pulse \(~260\text{nA}\), or \(13\mu\text{V}\) into a 500Ω load!!

'white' amplifier noise too high for a fast counter (~500MHz bandwidth)

=> need detector 'internal gain'

*see Webb, McIntyre, Conradi RCA Rev 35 1974
APD Gain...

Perkin Elmer 5*5mm$^2$
C30626 APD

For hard X ray detection, APD is used in semi-proportional gain mode, NOT as an avalanche counter

$\Rightarrow$ energy resolution possible

Gain
• increases logarithmically with voltage bias

• decreases with rising temperature
For constant gain, need compensation $\Delta V = 1.33\% / ^\circ C$ (gain = 100)

$\Delta V = 0.65\% / ^\circ C$ (gain = 20)
...and ‘Speed’

preamp signal output

Fe-55 (5.9keV) and Cd-109 (22.4keV)

Single X-ray pulses

gain ratio $\approx 4$ ‘correct’

FWHM of pulses $\approx 3$ ns
Specifications for a fast Silicon Avalanche Photodiode counter:

- Energy range < 3 keV (preamp noise threshold limit) up to Si absorption limit ~ 30keV ✓
- Counting rate > 10^7 cps ✓
- Time resolution < 1ns (silicon interaction depth-drift time limit) ✓
- Dark noise < 0.1 cps ✓
- Energy resolution ~ 20 % (separate of fluorescence and elastic scatter) ✓

- EASY TO USE, COMPLETE HARD- SOFTWARE SYSTEM ✓
- AVAILABLE TO ALL USERS AT AT ESRF AND BEYOND ✓
  (36 APD heads and 26 ACE modules)
ESRF APD system

APD head / preamplifier

Hamamatsu 5*3mm²
thickness 135µm
(absorption 45% at 12 keV )

or

Perkin-Elmer 5*5 and 10*10mm²
thickness 110µm (215µm)
ESRF Heads

Pekin-Elmer 10*10mm²
thickness 110µm (215µm)
Transmission mode

Hamamatsu 5*3mm²
thickness 135µm
(absorption 45% at 12 keV)
and Perkin-Elmer 5*5
thickness 110µm
Head = APD + Pre-amplifier

- Low noise 3 stage amplifier mmic (Agilent) ~ 500MHz BW
- Thermally stable (temperature feedback stabilization possible)
- Compact (<300mW)
- Compatible with Perkin-Elmer and Hamamatsu APDs (15... 120pF)
- STABLE AGAINST OSCILLATION !!
Base line restoration to remove AC coupling offsets.
Double (window) discriminators
Fixed dead time generator.
Pulse Pile-up and base line restoration

RF preamp stages are a-c coupled, so ‘average baseline’ evolves with X-ray count rate

Schottky diode (non-linear) baseline restorer:

Error (%)

Frequency input (Hz)
ACE (APD Controller Electronics) NIM unit

• Internal counter, 100MHz (180MHz / 10 pulse burst rate)
• External event synchronization: Trigger and gate input-output, direct SCA outputs (TTL and NIM)
• Energy Spectrum inspection by DAC controlled window discriminator scan
• Bias current measurement for count saturation indicator and overload safety--passive load plus HV feedback adjust
• Local control/display by graphic LCD with touch panel.
• Beamline remote control and data acquisition (‘SPEC’ software) via RS232/422 or GPIB.

(APD temperature measurement for gain compensation and device safety)
ESRF APD System: Count rate performance

ESRF uniform fill mode ID2 beamline tests at 12.5 keV
Hamamatsu 5x3mm² APD, nonparalyzable model fit
Energy resolution vs Gain

The energy resolution (FWHM) versus bias voltage is:

- Bias = 390V Energy resolution = 21% (optimal value for 6KeV)
- Bias = 360V Energy resolution = 21.5%
- Bias = 340V Energy resolution = 21.6%
- Bias = 310V Energy resolution = 22.7%
- Bias = 280V Energy resolution = 27%
Energy resolution vs Gain (bis)

The energy resolution (FWHM) versus bias voltage is:
- Bias = 380V Energy resolution = no measurement (saturation of input)
- Bias = 360V Energy resolution = 26.6%
- Bias = 340V Energy resolution = 24%
- Bias = 310V Energy resolution = 22%
- Bias = 280V Energy resolution = 18.5%
- Bias = 240V Energy resolution = 17% (optimal value for 22KeV)
- Bias = 200V Energy resolution = 20%

Cd-109 22/25keV
Energy resolution vs. (Output) Count Rate

ACE window mode SCA scan, 52Mcps OCR
energy resolution (E=12.5keV): $\Delta E/E = 39\%$
(Peak energy shift $\Delta V/V = -8\%$)
Commercialisation

- Licensing agreement between ESRF and Cyberstar (Oxford Danfysik catalogue distribution)

- NSLS (Brookhaven) basic NIM module, also produced by Cyberstar for Oxford Danfysik
Comparison of APD to YAP and NaI scintillator.

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<thead>
<tr>
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<th>NaI(Tl)</th>
<th>YAP:Ce</th>
<th>APD</th>
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<tbody>
<tr>
<td>Active area</td>
<td>5cm²</td>
<td>5cm²</td>
<td>0.15 -1cm²</td>
</tr>
<tr>
<td>Energy range</td>
<td>5keV…</td>
<td>5…60keV</td>
<td>3…30keV</td>
</tr>
<tr>
<td>Energy resolution @ 22keV</td>
<td>28%</td>
<td>56%</td>
<td>20-30%</td>
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<tr>
<td>Dynamic with dead time correction</td>
<td>400Khz</td>
<td>3Mhz</td>
<td>50Mhz</td>
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<tr>
<td>Dead time</td>
<td>1µs</td>
<td>0.11µs</td>
<td>0.006 µs</td>
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<tr>
<td>Linearity @ 1% dead time</td>
<td>10K</td>
<td>100khz</td>
<td>2Mhz</td>
</tr>
<tr>
<td>Linearity @ 5% dead time</td>
<td>50K</td>
<td>450khz</td>
<td>9Mhz</td>
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ESRF beamline ID31 (A Fitch)
...Resolution...

C30626, Fe-55 source (Mn K$_\alpha$, at 5.9, 6.4keV)

Resolution is dependent upon

- Fano statistics of photon absorption (~photon energy$^{1/2}$)
- Multiplication noise (~APD internal gain$^2$)
- Preamplifier noise (~bandwidth$^{1/2}$)
Future?

- APD arrays and telescopes

- custom head packaging (vacuum, cryogenic...?)

- faster counting --> 350 MHz 'ESRF machine limit'