2456-4

Joint ICTP-IAEA Workshop on Advances in Digital Spectroscopy

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Neutrons

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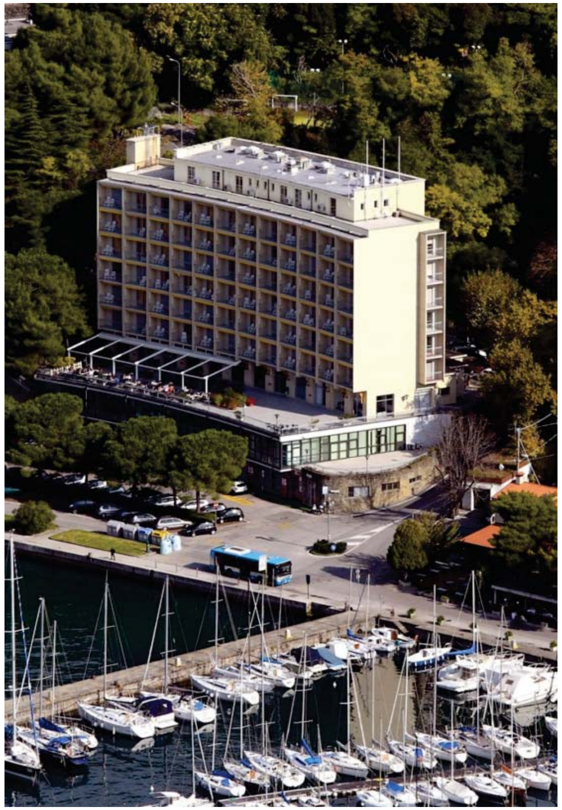
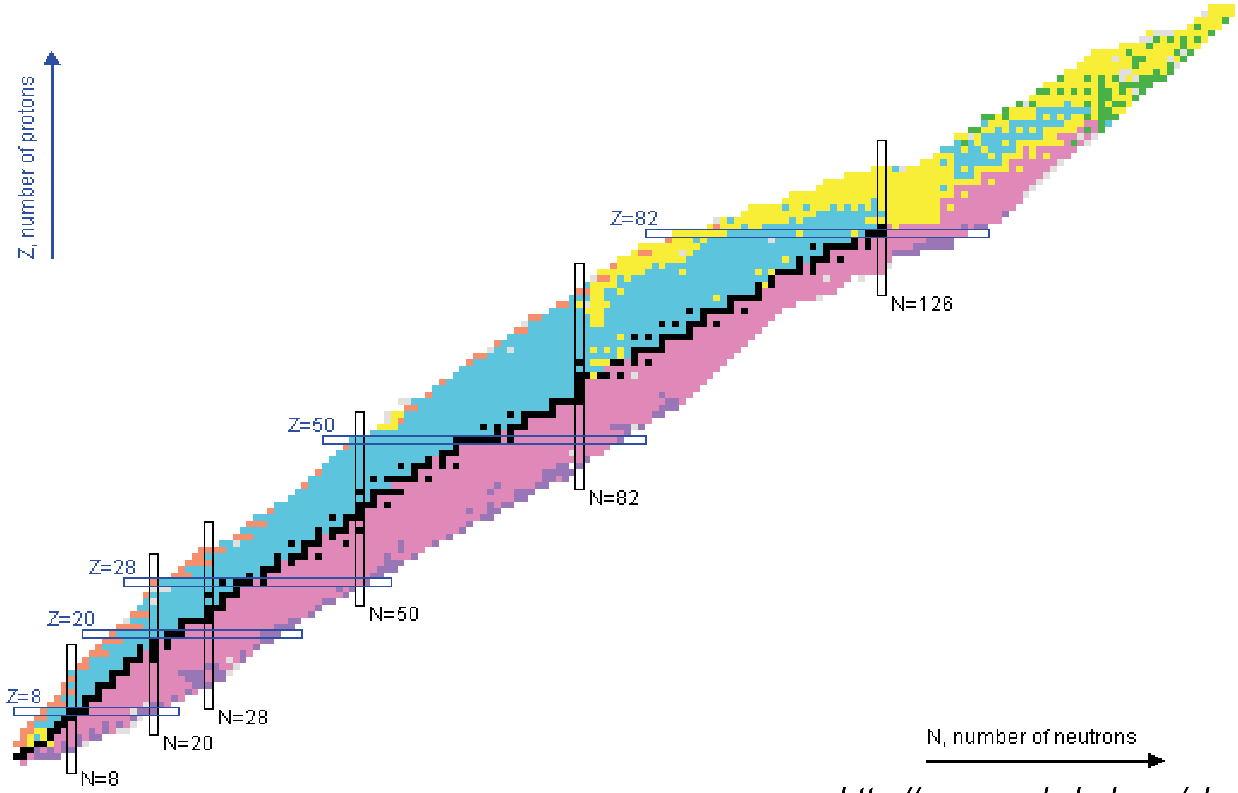
Essentials of digital neutron detectors

Robert Grzywacz
(University of Tennessee/ORNL)

- Neutron sources
- Neutron detectors
- Some digital techniques
- What do we use tomorrow in the lab



Neutron – a basic building block of atomic nucleus



http://www.nndc.bnl.gov/chart/

It is not easy to see a "free" neutron !
Always confined in a nucleus.
It decays with $T_{1/2}$ ~ 10.183 min because it is heavier than proton ($E=mc^2$=782 keV).
Because q=0 it is very difficult to detect, it hardly interacts with matter.

The chain of discoveries

Discovery of the alpha particle
from the radioactive decay.
(Rutherford 1903)

Discovery of the neutron
via bombarding beryllium
with alpha particles from polonium.
(Chadwick 1932) $\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$

Hahn and Strassman (1938)
use the neutrons to irradiate
uranium, barium is observed.

$${}^{140}Xe \rightarrow {}^{140}Cs \rightarrow {}^{140}Ba \rightarrow {}^{140}La \rightarrow {}^{140}Ce\,(stable)$$

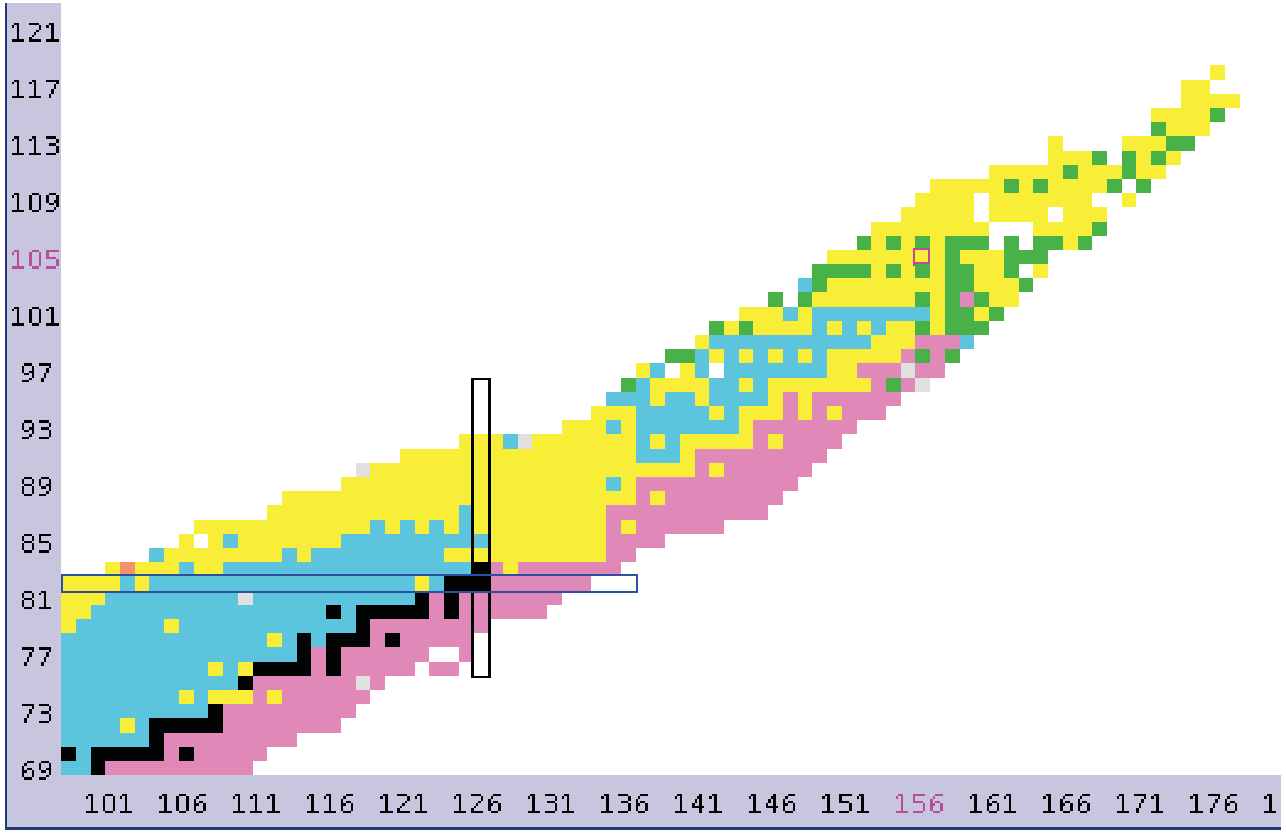
Meitner and Frisch (1939)
interpret it as ***fission***

Bohr and Wheeler (1939)
explain the fission on
the basis of the liquid drop model

Petrzhak and Flerov (1940)
discover spontaneous fission

Fermi builds first reactor
1942 using chain reaction

Nuclear Fission



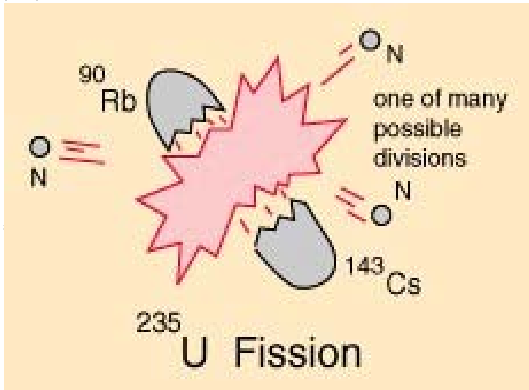
http://www.nndc.bnl.gov/chart/

Spontaneous fission as a source of neutrons

Table 11-1. Spontaneous fission neutron yields

Isotope A	Number of Protons Z	Number of Neutrons N	Total Half-Life[a]	Spontaneous Fission Half-Life[b] (yr)	Spontaneous Fission Yield[b] (n/s-g)	Spontaneous Fission Multiplicity[b,c] ν	Induced Thermal Fission Multiplicity[c] ν
^{232}Th	90	142	1.41×10^{10} yr	$>1 \times 10^{21}$	$>6 \times 10^{-8}$	2.14	1.9
^{232}U	92	140	71.7 yr	8×10^{13}	1.3	1.71	3.13
^{233}U	92	141	1.59×10^{5} yr	1.2×10^{17}	8.6×10^{-4}	1.76	2.4
^{234}U	92	142	2.45×10^{5} yr	2.1×10^{16}	5.02×10^{-3}	1.81	2.4
^{235}U	92	143	7.04×10^{8} yr	3.5×10^{17}	2.99×10^{-4}	1.86	2.41
^{236}U	92	144	2.34×10^{7} yr	1.95×10^{16}	5.49×10^{-3}	1.91	2.2
^{238}U	92	146	4.47×10^{9} yr	8.20×10^{15}	1.36×10^{-2}	2.01	2.3
^{237}Np	93	144	2.14×10^{6} yr	1.0×10^{18}	1.14×10^{-4}	2.05	2.70
^{238}Pu	94	144	87.74 yr	4.77×10^{10}	2.59×10^{3}	2.21	2.9
^{239}Pu	94	145	2.41×10^{4} yr	5.48×10^{15}	2.18×10^{-2}	2.16	2.88
^{240}Pu	94	146	6.56×10^{3} yr	1.16×10^{11}	1.02×10^{3}	2.16	2.8
^{241}Pu	94	147	14.35 yr	(2.5×10^{15})	(5×10^{-2})	2.25	2.8
^{242}Pu	94	148	3.76×10^{5} yr	6.84×10^{10}	1.72×10^{3}	2.15	2.81
^{241}Am	95	146	433.6 yr	1.05×10^{14}	1.18	3.22	3.09
^{242}Cm	96	146	163 days	6.56×10^{6}	2.10×10^{7}	2.54	3.44
^{244}Cm	96	148	18.1 yr	1.35×10^{7}	1.08×10^{7}	2.72	3.46
^{249}Bk	97	152	320 days	1.90×10^{9}	1.0×10^{5}	3.40	3.7
^{252}Cf	98	154	2.646 yr	85.5	2.34×10^{12}	3.757	4.06

[a]Ref. 1.
[b]Ref. 2. Values in parentheses are from Ref. 3 and have estimated accuracies of two orders of magnitude. Pu-240 fission rate is taken from Refs. 4 and 5.
[c]Ref. 6.



http://hyperphysics.phy-astr.gsu.edu
/hbase/nucene/fission.html

Passive Nondstructive Assay of Nuclear Materials
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NuREG/cR-5550 LA-UR-90-732
http://www.lanl.gov/orgs/n/n1/panda/

The ^{252}Cf source

Table 11-7. Characteristics of ^{252}Cf

Total half-life	2.646 yr
Alpha half-life	2.731 yr
Spontaneous fission half-life	85.5 yr
Neutron yield	2.34×10^{12} n/s-g
Gamma-ray yield	1.3×10^{13} γ/s-g
Alpha-particle yield	1.9×10^{13} α/s-g
Average neutron energy	2.14 MeV
Average gamma-ray energy	1 MeV
Average alpha-particle energy	6.11 MeV
Neutron activity	4.4×10^{9} n/s-Ci
Neutron dose rate	2300 rem/h-g at 1 m
Gamma dose rate	140 rem/h-g at 1 m
Conversion	558 Ci/g
Decay heat	38.5 W/g
Avg. spontaneous fission neutron multiplicity	3.757
Avg. spontaneous fission gamma multiplicity	8

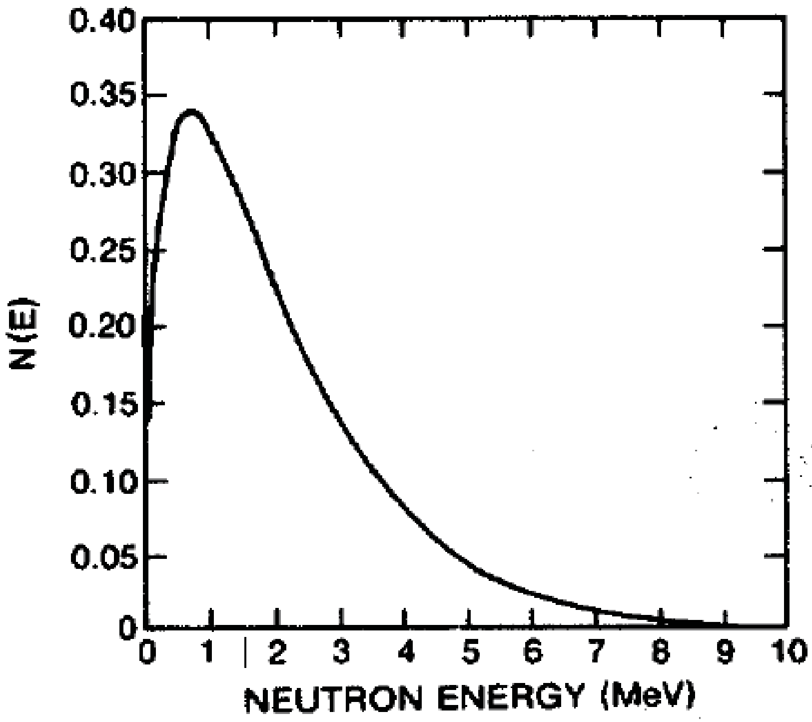
	253Fm 3.00 D ϵ: 88.00% α: 12.00%	254Fm 3.240 H α: 99.94% SF: 0.06%	255Fm 20.07 H α: 100.00% SF: 2.4E-5%	256Fm 157.6 M SF: 91.90% α: 8.10%	257F 100.5 α: 99. SF: 0.
	252Es 471.7 D α: 78.00% ϵ: 22.00%	253Es 20.47 D α: 100.00% SF: 8.7E-6%	254Es 275.7 D α: 100.00% β-: 1.7E-4%	255Es 39.8 D β-: 92.00% α: 8.00%	256E 25.4 β-: 100
SF: 0.08%	251Cf 898 Y α: 100.00% SF	252Cf 2.645 Y α: 96.91% SF: 3.09%	253Cf 17.81 D β-: 99.69% α: 0.31%	254Cf 60.5 D SF: 99.69% α: 0.31%	255C 85 M β-: 100
249Bk 330 D β-: 100.00% α: 1.4E-3%	250Bk 3.212 H β-: 100.00%	251Bk 55.6 M β-: 100.00%	252Bk	253Bk β-	254E
248Cm 3.48E+5 Y	249Cm 64.15 M	250Cm ≈8.3E+3 Y	251Cm 16.8 M	252Cm <2 D	

^{252}Cf source has to be handled with extreme care !

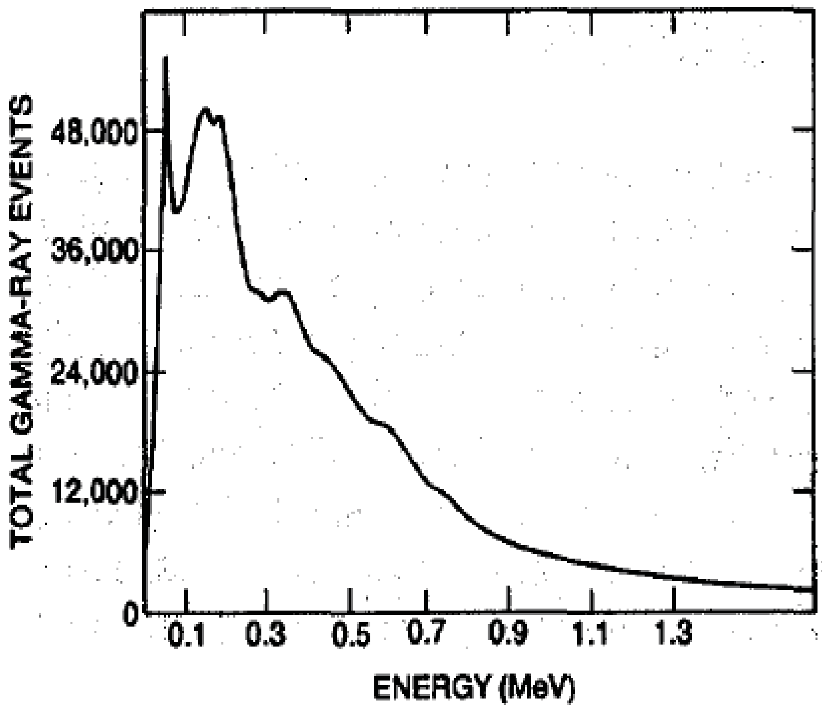
The ^{252}Cf source

Neutron energy spectrum
(Maxwellian distribution)

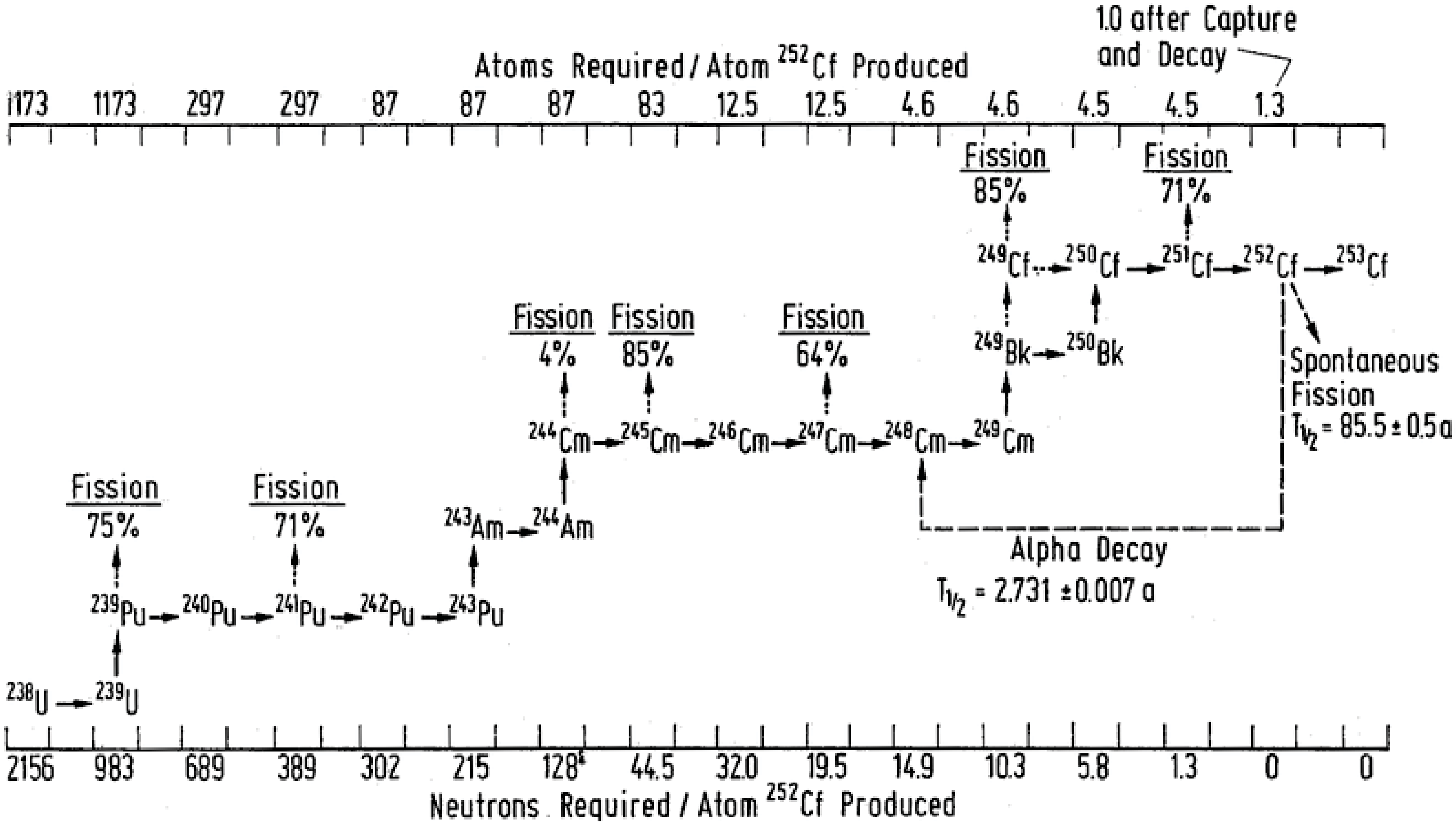
$$N(E) = E^{1/2} \exp(-E/1.43\ \text{MeV})$$



Gamma-ray spectrum



Production of ^{252}Cf at High Flux Isotope Reactor (Oak Ridge)



^{252}Cf is a commonly used source of neutrons – for industrial applications !

Neutrons from reactions

Alpha-n nueutron sources

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$$

Table 11-5. Thick-target yields from (α,n) reactions (error bars estimated from scatter between references)

Element (Natural Isotopic Composition)	Neutron Yield per 10^6 Alphas of Energy 4.7 MeV (^{234}U)	Neutron Yield per 10^6 Alphas of Energy 5.2 MeV (av. Pu)	References	Av. Neutron Energy (MeV) for 5.2 MeV Alphas (Ref. 29)
Li	0.16 ± 0.04	1.13 ± 0.25	30	0.3
Be	44 ± 4	65 ± 5	31	4.2
B	12.4 ± 0.6	17.5 ± 0.4	29, 30, 33	2.9
C	0.051 ± 0.002	0.078 ± 0.004	29, 30, 31	4.4
O	0.040 ± 0.001	0.059 ± 0.002	29, 30, 31	1.9
F	3.1 ± 0.3	5.9 ± 0.6	29, 30, 33	1.2
Na	0.5 ± 0.5	1.1 ± 0.5	32	
Mg	0.42 ± 0.03	0.89 ± 0.02	29, 30, 31	2.7
Al	0.13 ± 0.01	0.41 ± 0.01	29, 30, 31	1.0
Si	0.028 ± 0.002	0.076 ± 0.003	29, 30, 31	1.2
Cl	0.01 ± 0.01	0.07 ± 0.04	32	

Alpha-n nueutron sources

Neutron source can be made by mixing source of alphas with target material. AmBe, PuBe, AmLi ...

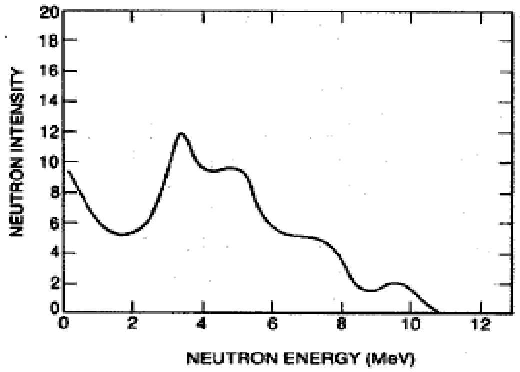


Fig. 11.4 Typical neutron spectrum of an AmBe source.

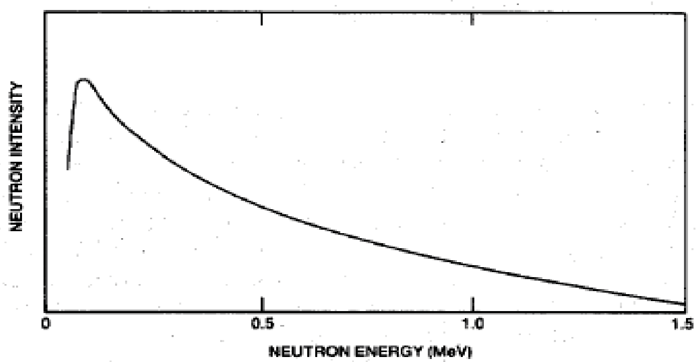


Fig. 11.5 Typical neutron energy spectrum of an AmLi source.

Alpha-n nueutron sources

Table 11-3. (Alpha,n) reaction neutron yields

Isotope A	Total Half-Life[a]	Alpha Decay Half-Life[a]	Alpha Yield[a] (α/s-g)	Average Alpha Energy[a] (MeV)	(α,n) Yield in Oxide[b] (n/s-g)	(α,n) Yield in UF_6/PuF_4[c] (n/s-g)
^{232}Th	1.41×10^{10} yr	1.41×10^{10} yr	4.1×10^{3}	4.00	2.2×10^{-5}	
^{232}U	71.7 yr	71.7 yr	8.0×10^{11}	5.30	1.49×10^{4}	2.6×10^{6}
^{233}U	1.59×10^{5} yr	1.59×10^{5} yr	3.5×10^{8}	4.82	4.8	7.0×10^{2}
^{234}U	2.45×10^{5} yr	2.45×10^{5} yr	2.3×10^{8}	4.76	3.0	5.8×10^{2}
^{235}U	7.04×10^{8} yr	7.04×10^{8} yr	7.9×10^{4}	4.40	7.1×10^{-4}	0.08
^{236}U	2.34×10^{7} yr	2.34×10^{7} yr	2.3×10^{6}	4.48	2.4×10^{-2}	2.9
^{238}U	4.47×10^{9} yr	4.47×10^{9} yr	1.2×10^{4}	4.19	8.3×10^{-5}	0.028
^{237}Np	2.14×10^{6} yr	2.14×10^{6} yr	2.6×10^{7}	4.77	3.4×10^{-1}	
^{238}Pu	87.74 yr	87.74 yr	6.4×10^{11}	5.49	1.34×10^{4}	2.2×10^{6}
^{239}Pu	2.41×10^{4} yr	2.41×10^{4} yr	2.3×10^{9}	5.15	3.81×10^{1}	5.6×10^{3}
^{240}Pu	6.56×10^{3} yr	6.56×10^{3} yr	8.4×10^{9}	5.15	1.41×10^{2}	2.1×10^{4}
^{241}Pu	14.35 yr	5.90×10^{5} yr	9.4×10^{7}	4.89	1.3	1.7×10^{2}
^{242}Pu	3.76×10^{5} yr	3.76×10^{5} yr	1.4×10^{8}	4.90	2.0	2.7×10^{2}
^{241}Am	433.6 yr	433.6 yr	1.3×10^{11}	5.48	2.69×10^{3}	
^{242}Cm	163 days	163 days	1.2×10^{14}	6.10	3.76×10^{6}	
^{244}Cm	18.1 yr	18.1 yr	3.0×10^{12}	5.80	7.73×10^{4}	
^{249}Bk	320 days	6.1×10^{4} yr	8.8×10^{8}	5.40	1.8×10^{1}	
^{252}Cf	2.646 yr	2.731 yr	1.9×10^{13}	6.11	6.0×10^{5}	

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Alpha-n neutron sources

Table 11-8. Characteristics of some isotopic (α,n) sources

Source	Half-Life[a] (yr)	Average Alpha Energy[a] (MeV)	Average Neutron Energy[a] (MeV)	Maximum Neutron Energy[b] (MeV)	Gamma Dose in mrem/h at 1 m/(10^6 n/s)[c]	Curies per Gram[d]	Yield in 10^6 n/s-Ci[c]
^{210}PoBe	0.38	5.3	4.2	10.9	0.01	4490	2-3
^{226}RaBe	1600	4.8	4.3	10.4	60	1	0-17
^{238}PuBe	87.74	5.49	4.5	11.0	0.006	17	2-4
^{238}PuLi	87.74	5.49	0.7	1.5	~1	17	0.07
$^{238}PuF_4$	87.74	5.49	1.3	3.2	~1	17	0.4
$^{238}PuO_2$	87.74	5.49	2.0	5.8	~1	17	0.003
^{239}PuBe	24 120.	5.15	4.5	10.7	6	0.06	1-2
$^{239}PuF_4$	24 120.	5.15	1.4	2.8	~1	0.06	0.2
^{241}AmBe	433.6	5.48	5.0	11.0	6	3.5	2-3
^{241}AmLi	433.6	5.48	0.3	1.5	2.5	3.5	0.06
^{241}AmB	433.6	5.48	2.8	5.0		3.5	
^{241}AmF	433.6	5.48	1.3	2.5		3.5	

[a]Ref. 1.
[b]Ref. 26.
[c]Ref. 36.
[d](Alpha yield/s-g)/(3.7×10^{10} dps/Ci).

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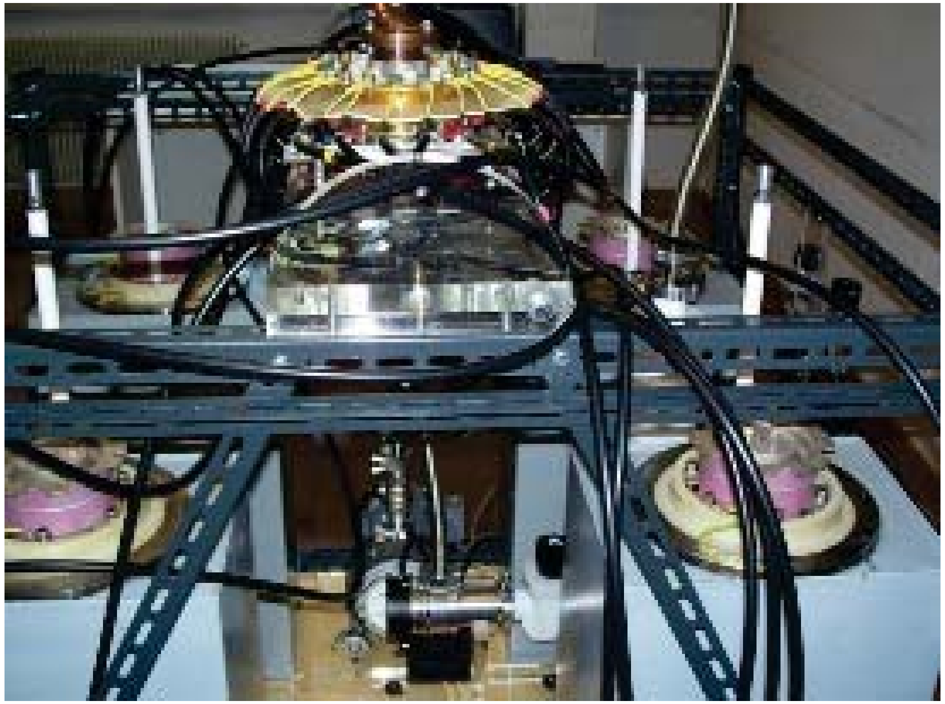
Neutron generators

$$D + T \rightarrow n + {}^4He \quad E_n = 14.1\ MeV$$

$$D + D \rightarrow n + {}^3He \quad E_n = 2.5\ MeV$$



Dense plasma focus !
(Prof. V. Gribkov)

Type of source	Neutron yield 14 MeV/2.5 MeV	Hard X-ray dose (at 1 m)	X-ray photon energy ranges	Pulse duration	Lifetime	DPF weight
Portable	~ 10^8 / 10^6 n/pulse	0.1 Rö	10 - 30 / 30 - 70 keV	3 - 5 ns	10^4 shots	~ 20 kg
Transportable	~ 10^{10} / 10^8 n/pulse	1.0 Rö	10 - 80 / 80 - 150 keV	10 - 15 ns	10^6 shots	~ 400 kg

Some terminology

0.0 ev - 0.025 ev Cold neutrons

~ 0.025 ev --> Thermal neutrons

0.025 ev - 0.4 ev --> Epithermal neutrons

0.4 ev - 0.6 ev --> Cadmium neutrons

0.6 ev - 1 ev --> EpiCadmium neutrons

1 ev - 10 ev --> Slow neutrons

10 ev - 300 ev --> Resonance neutrons

300 ev - 1 Mev --> Intermediate neutrons

1 Mev - 20 Mev --> Fast neutrons

E> 20 Mev --> Relativistic neutrons

Non-portable neutron sources

Nuclear reactors
Neutron induced fission
(“thermal” neutrons)

Accelerators
Alpha particle beams
Deuterons (d,n)
Spallation
(Variable energy, cold neutron

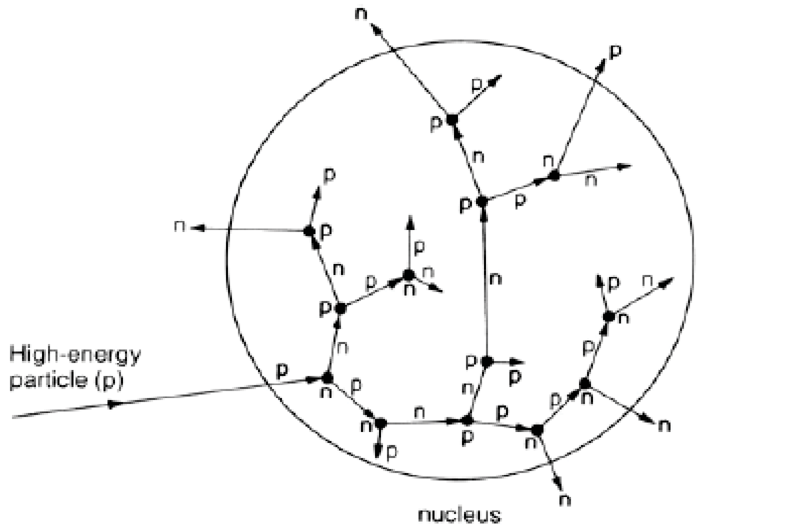
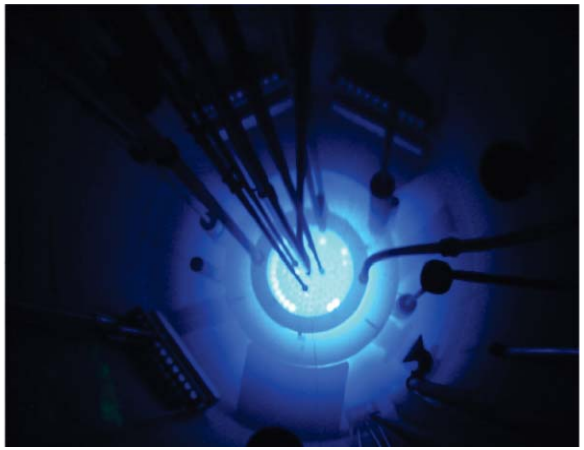


Figure 10.31 Schematic view of nuclear cascade. [From Lieser (1997).]



Neutron detection

Neutron doesn't carry electric charge !

The principal mode of interaction of neutron with material are:

- scattering
- reactions (radiative capture)

Scattering is a fundamental for “fast” neutron detection (~keV or larger)

Capture requires “thermalization” (slowing-down) of neutrons down to very low energies.

Reactions generating charged particle used for Neutron Detectors

$$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha \quad Q = 2.310\,MeV \quad 94\%$$
$$^{10}B + n \rightarrow {}^{7}Li + \alpha \quad Q = 2.792\,MeV \quad 6\%$$
$$^{6}Li + n \rightarrow {}^{3}H + \alpha \quad Q = 4.78\,MeV$$
$$^{3}He + n \rightarrow {}^{3}H + p \quad Q = 0.764\,MeV$$

The importance
of thermalization of neutrons:

Gas:
Boron Trifluoride (BF_3) and ^{3}He
Solids:
B,Li

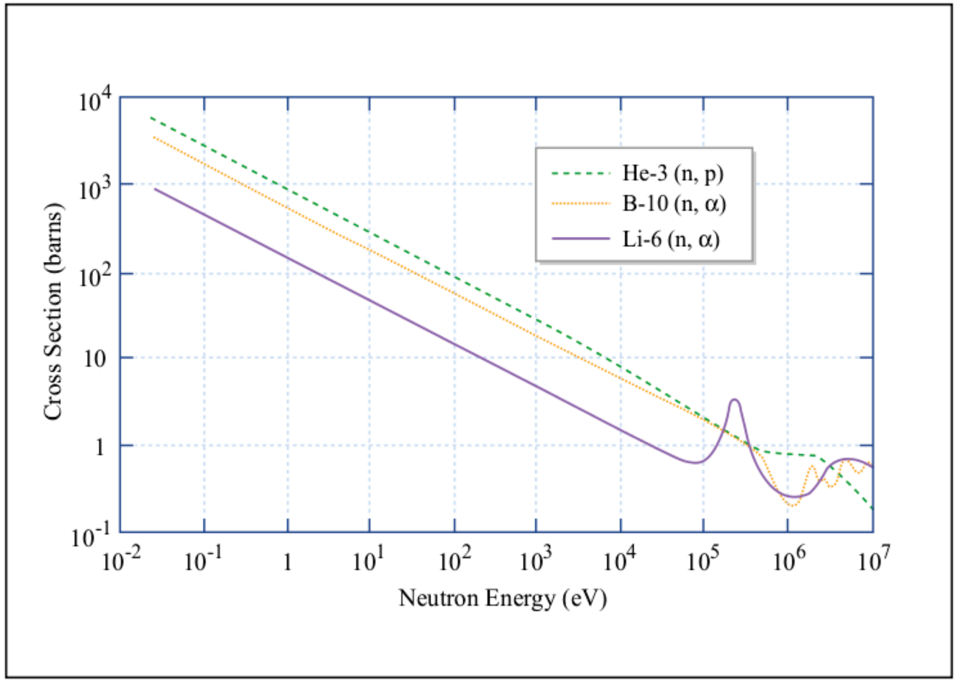
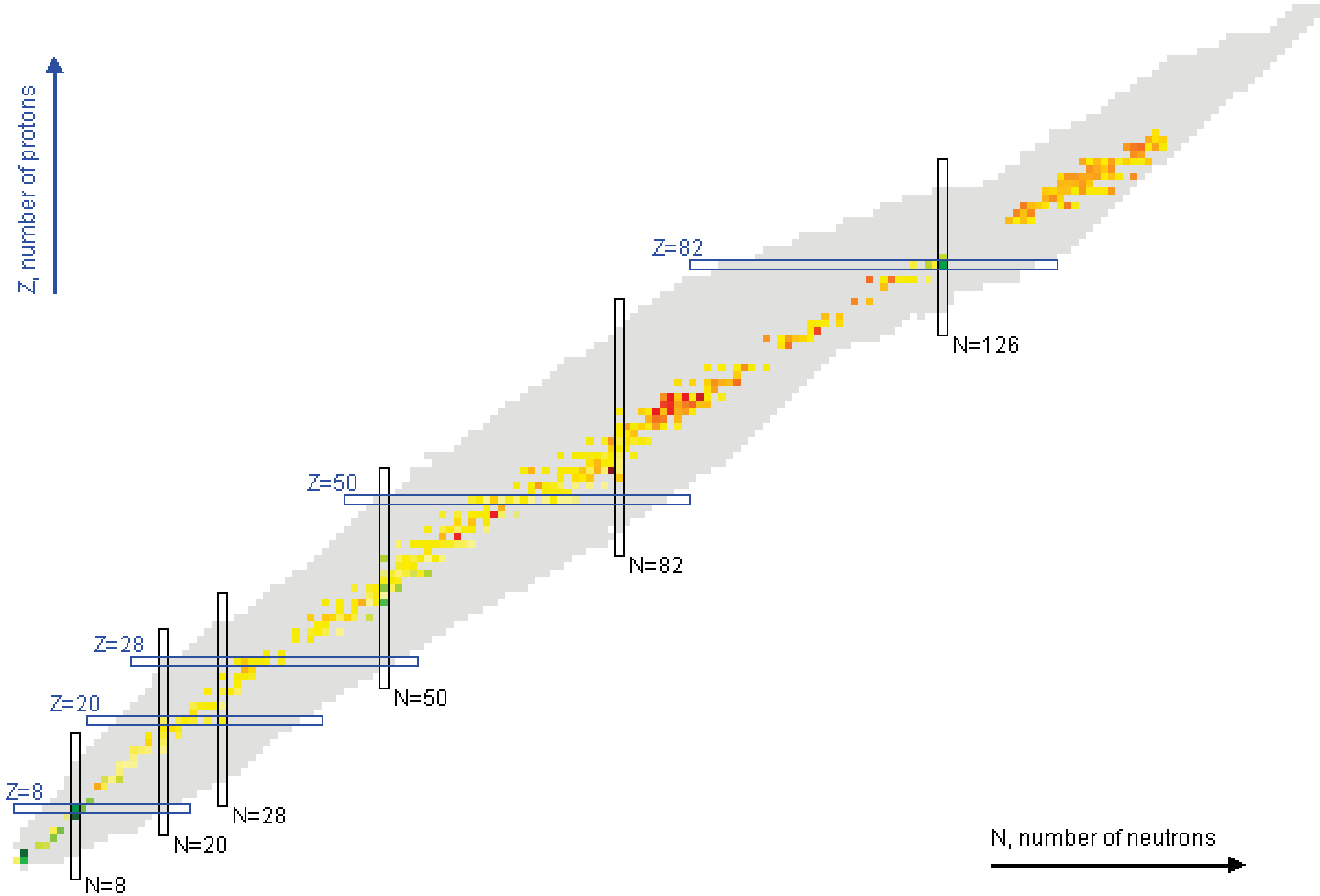


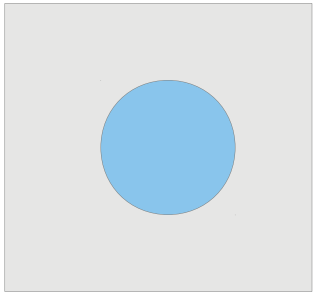
Image by MIT OpenCourseWare.

Radiative neutron (n,γ) capture cross-section



http://www.nndc.bnl.gov/chart/

The Neutron Counter



Proportional
gas (3He,BF3) counter
Inside moderator
(HDPE)

Neutron slowing down
may take 100µs

3Hen at ORN

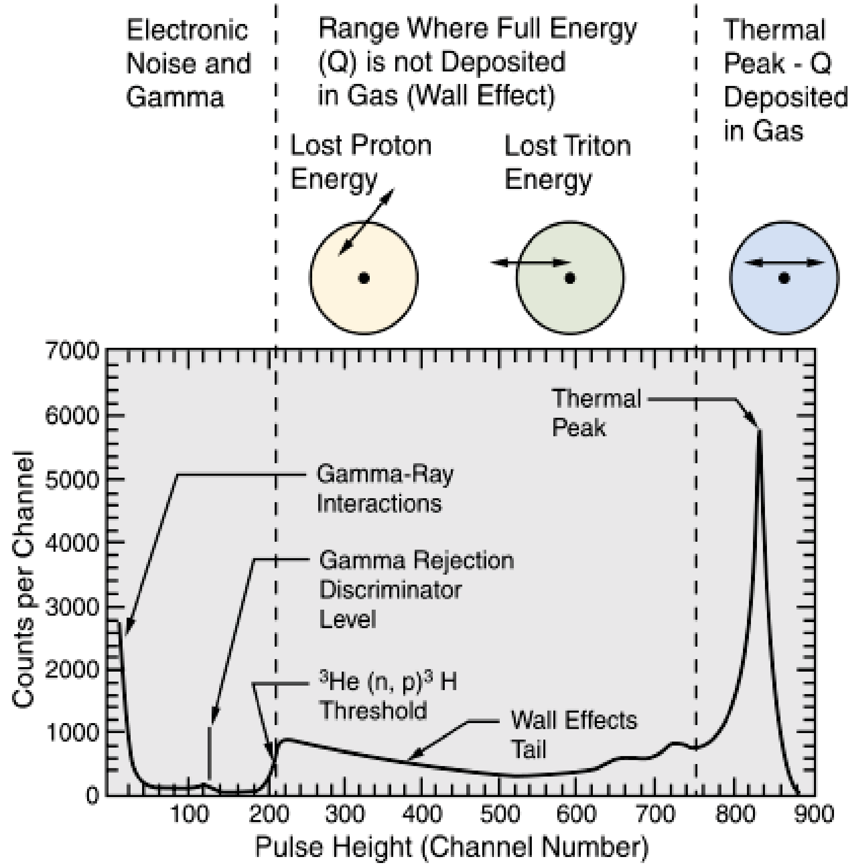
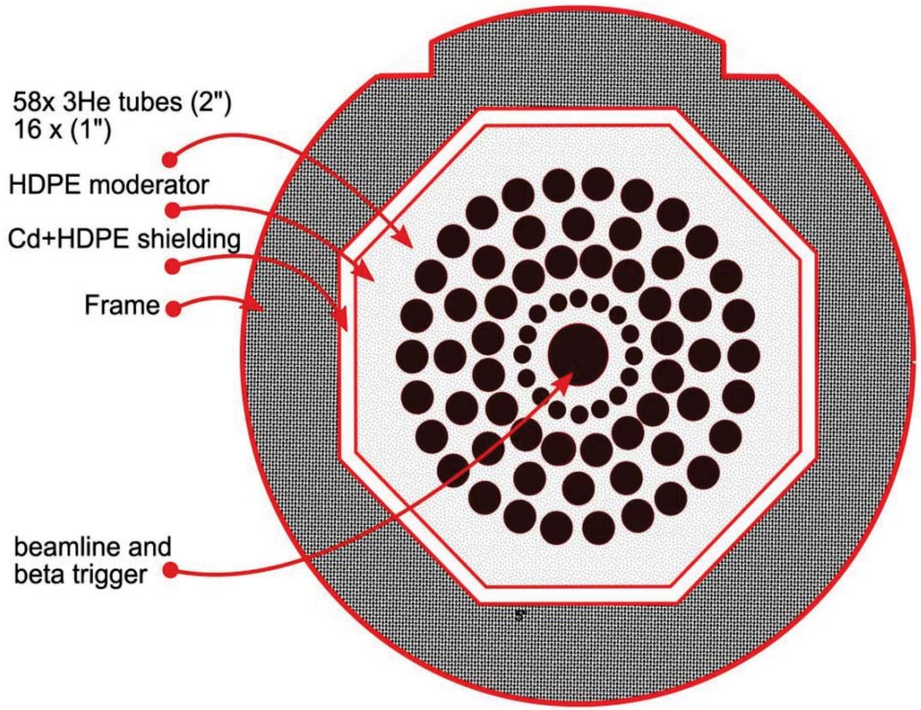
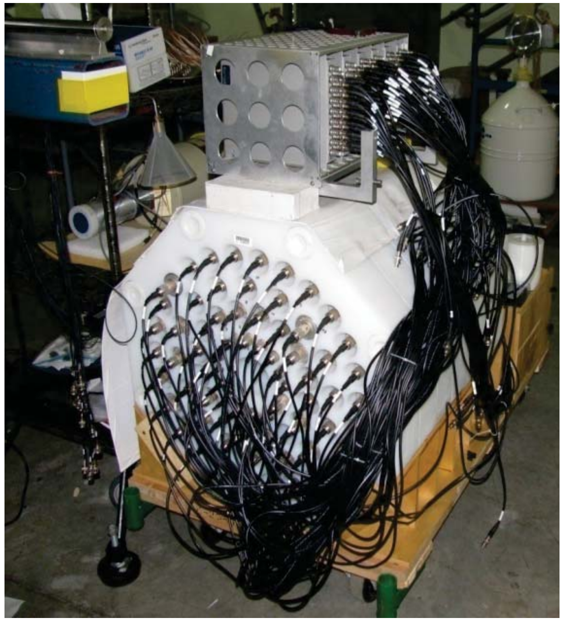


Figure 1.49 Thermal Neutron Induced Pulse Height Spectrum from a Moderated ^{3}He Detector

Canberra

The Digital Neutron Counter (3Hen at ORNL)





Neutron detection in scintillator

Neutron scatters of hydrogen and transfer parts of its kinetic energy onto charge particle (proton). The ionization induced in the material is detected.

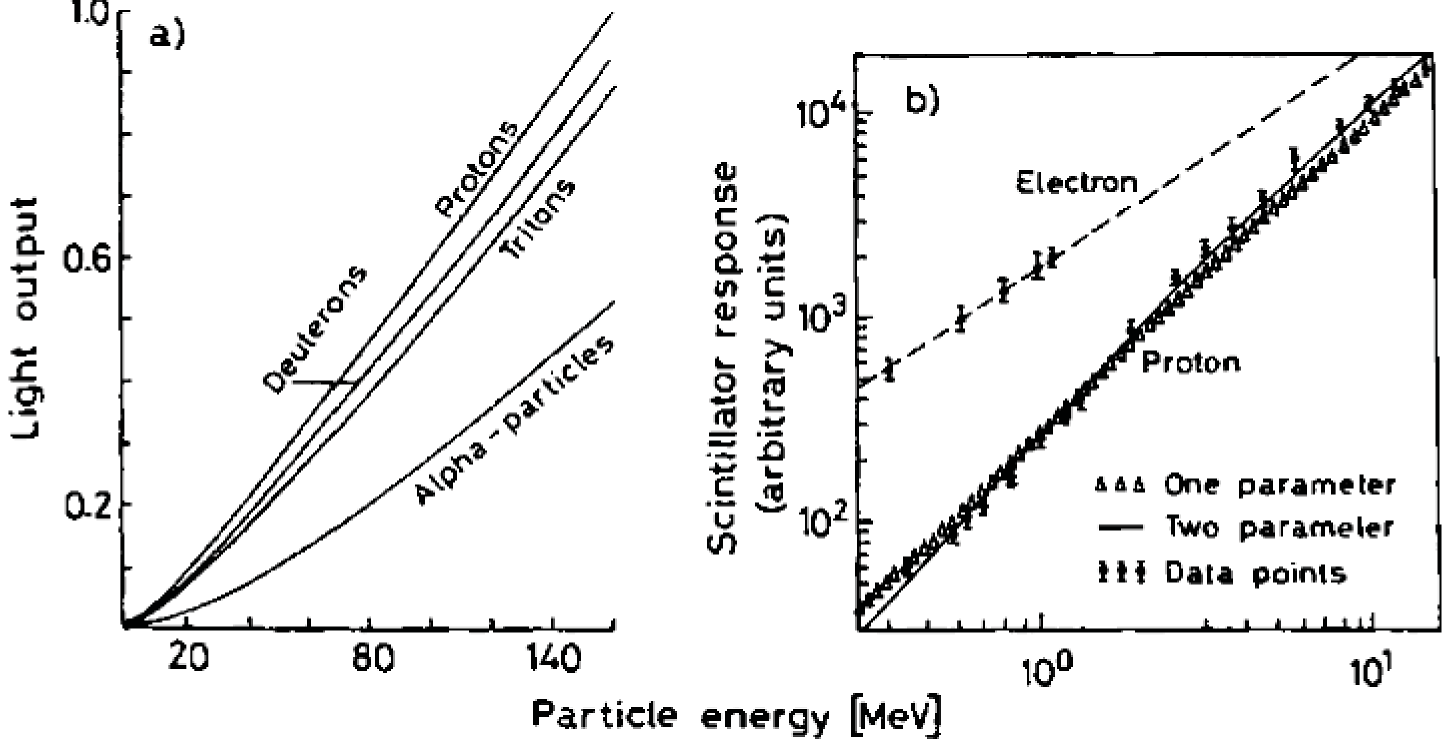
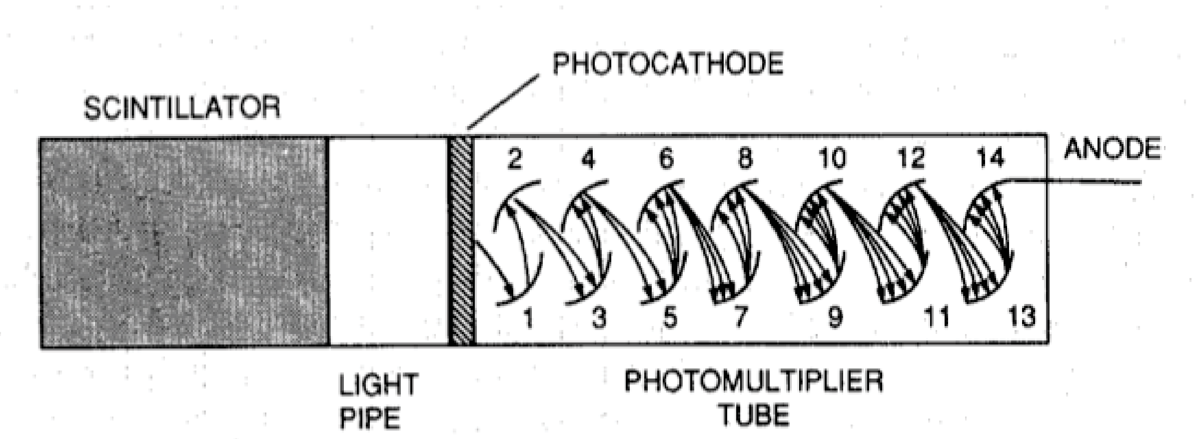


Fig. 7.8 a, b. Response of NE102 plastic scintillator to different particles ((a) from *Gooding* and *Pugh* [7.6]; (b) from *Craun* and *Smith* [7.7])

Scintillation detectors

Light induced in the scintillator material induces electrons on photocatode, this signal is amplified in a photomultiplier.



Neutron detecting scintillators:

Solid state (plastics)
Liquid organic scintillators.

http://www.detectors.saint-gobain.com/Liquid-Scintillator.aspx
http://www.eljentechnology.com/index.php/products

Neutron pulse-shape discrimination in liquid scintillators

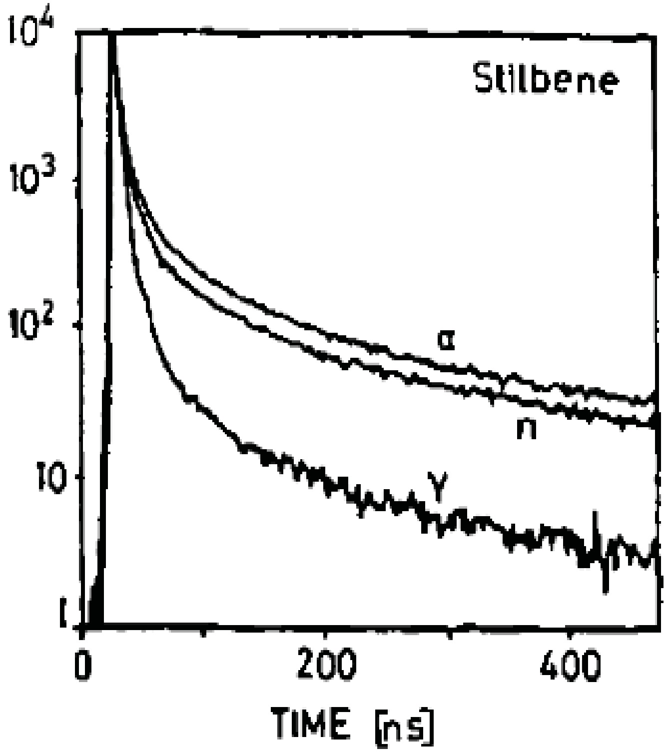


Fig. 7.11. Pulse shape of stilbene light for alpha particles, neutrons and gamma rays (from *Lynch* [7.71]; picture © 1975 IEEE)

Fast neutron detectors in nuclear research

Digital techniques in neutron detection

Neutron-gamma discrimination using pulse shape analysis (charge comparison, zero crossing methods)

High-resolution time of flight measurements

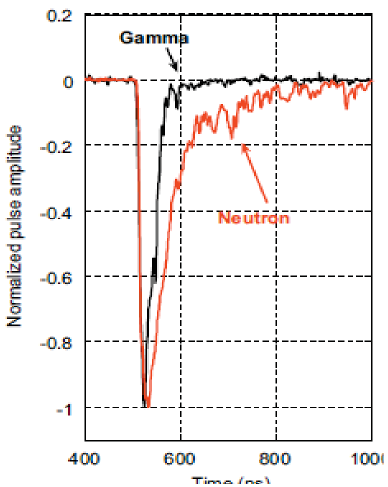
Neutron-gamma discrimination

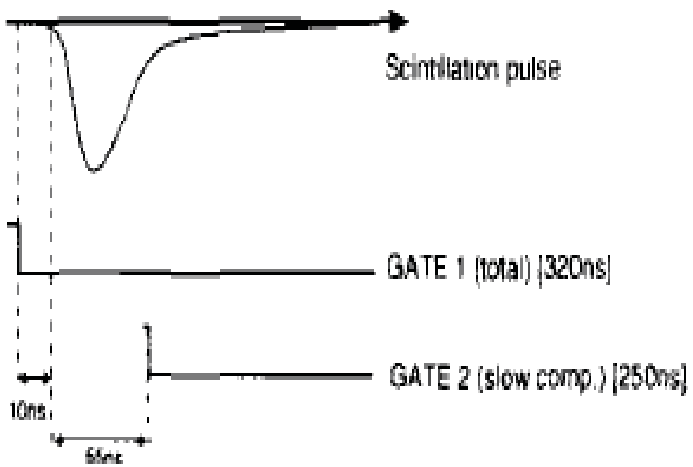
Neutron induced signals are "slower" due to delayed photon emission after ionization by heavy particle.

Classic n-g discrimination methods:

zero crossing, charge comparison

V.T.Jordanov,G.F.Knoll,IEEETrans.Nucl.Sci.NS-42(4)(1995)683.
S.Normand,B.Mouanda,S.Haan,M.Louvel,Nucl.Instr.andMeth.Phys.Res. A 484(2002)342.





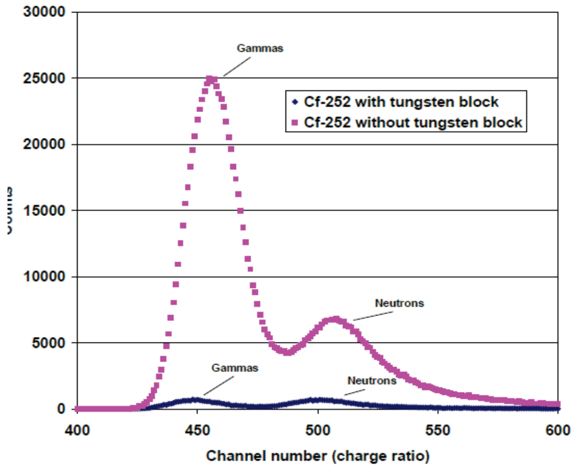


Figure 3. Distribution of PSD module calculated charge ratios for a Cf-2 source, with and without a tungsten gamma shield block.

Neutron time-of-flight detection principle

Photons always win the race !

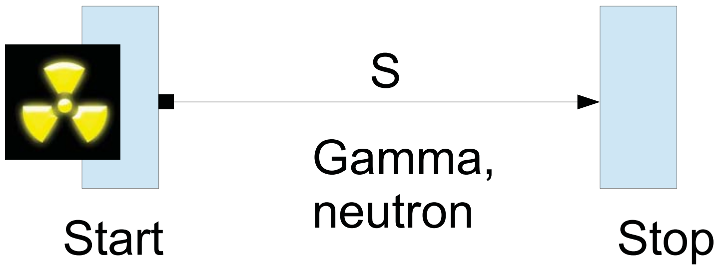
Neutrons:

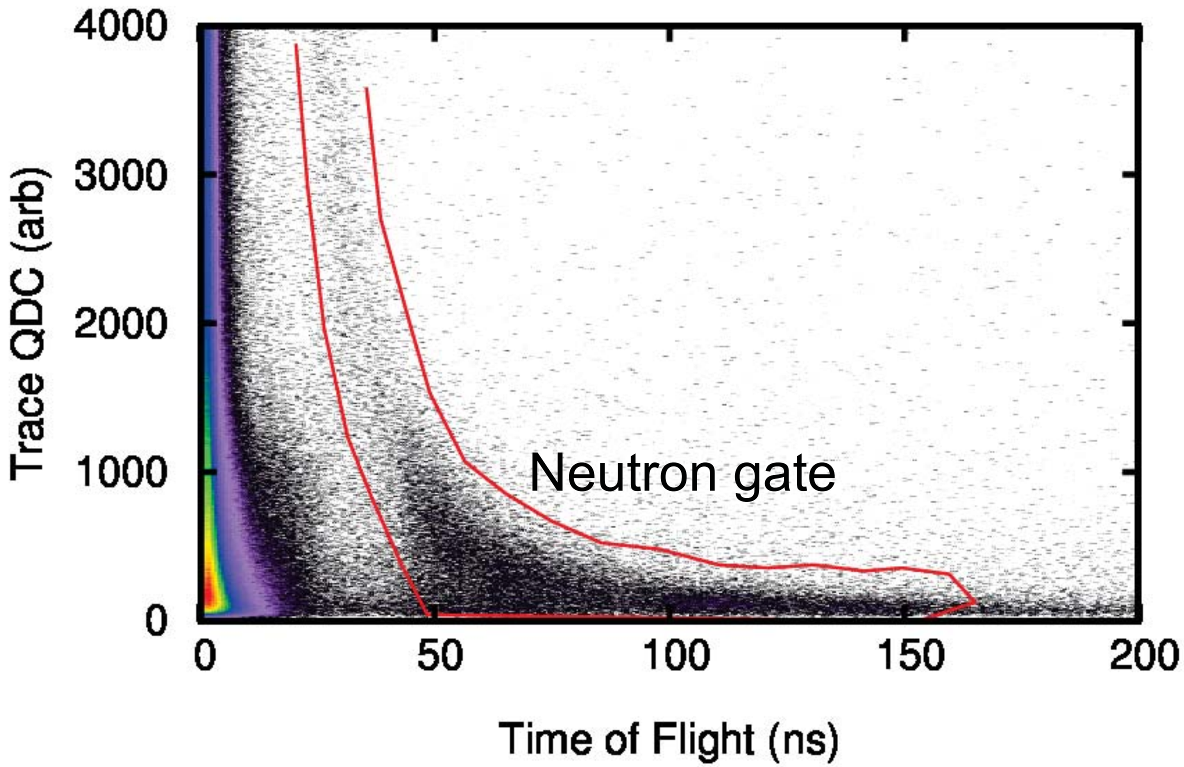
$$E=\frac{mv^2}{2} \qquad v=\frac{s}{TOF}$$

$$v=\sqrt{\frac{2E}{m}} \qquad TOF=s\sqrt{\frac{m}{2E}}$$

Photons:

V=c=const
TOF=const



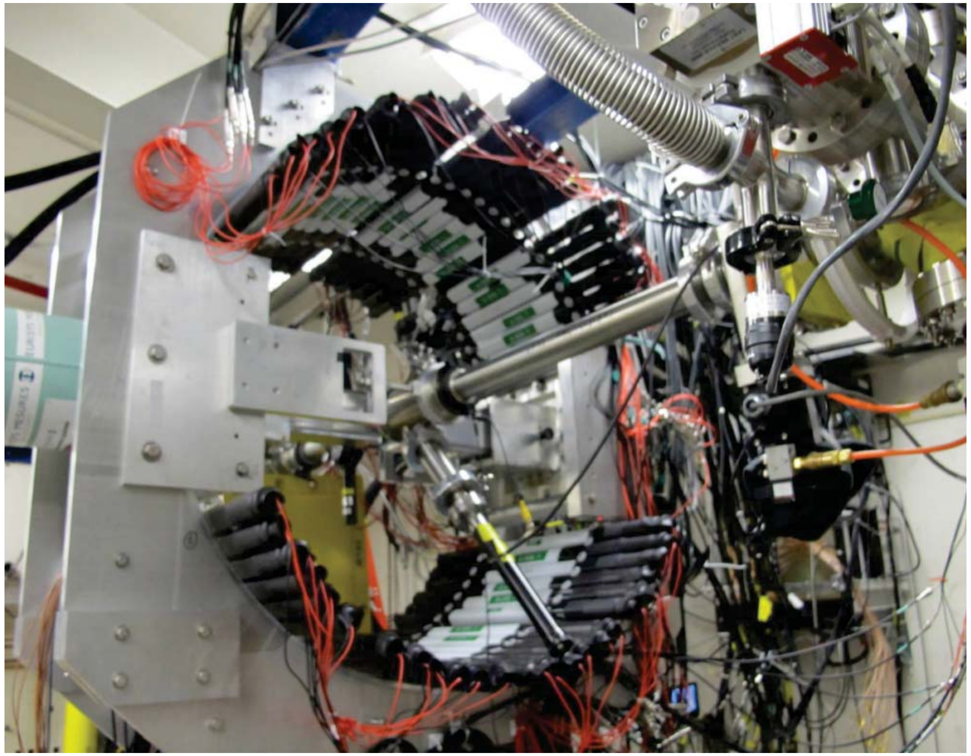


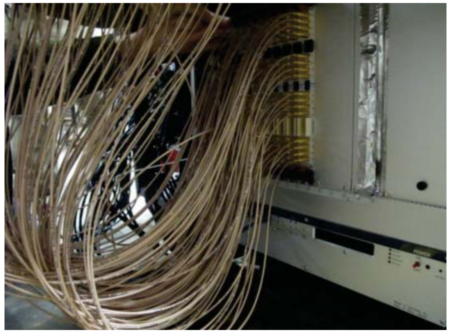
VANDLE – fully digital neutron array
The Versatile Array for Neutron Detection at Low Energies

- 2 clovers, 3% efficient @ 1MeV
- 48 x 60 cm VANDLE bars
  - 45% efficiency/bar @ 1MeV
  - Ω = 26% of 4π
  - 12% total efficiency @ 1MeV
- Fully instrumented using XIA's Pixie 16 digitizers
- Custom firmware:

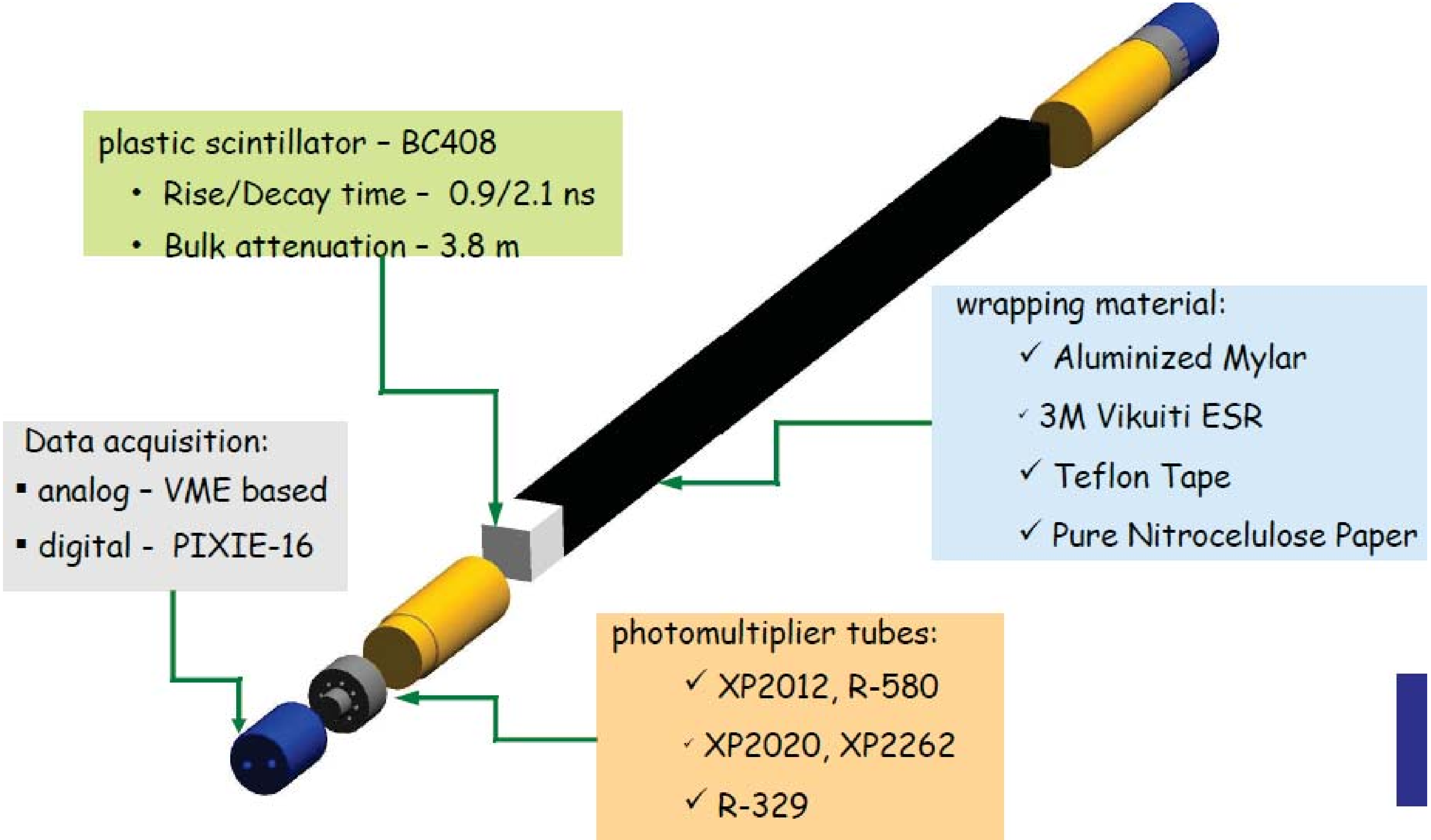
Triple-coincidence two-level triggering scheme

  - VANDLE pairwise coincidences (per bar)
  - Beta trigger required for readout



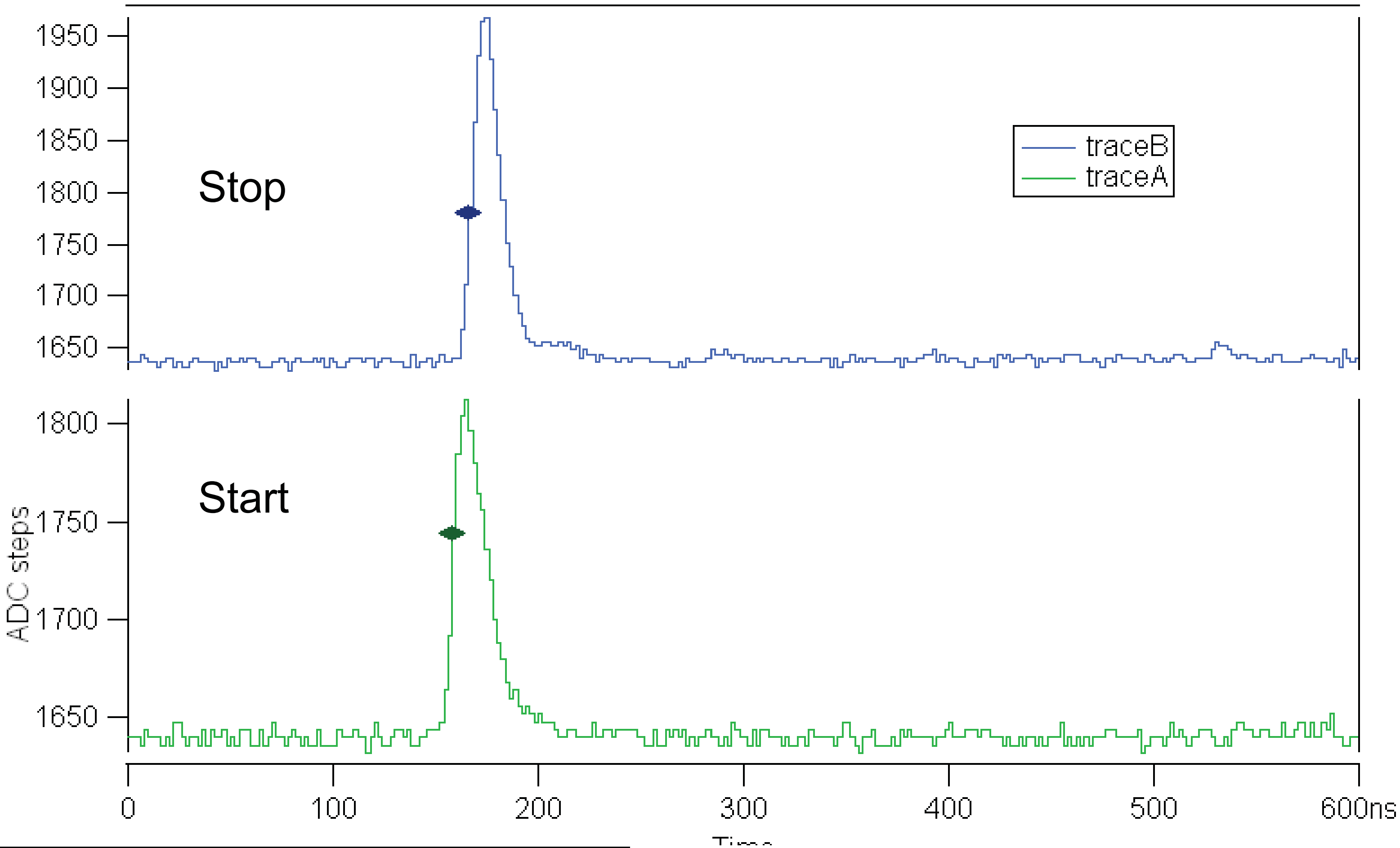


VANDLE detector module

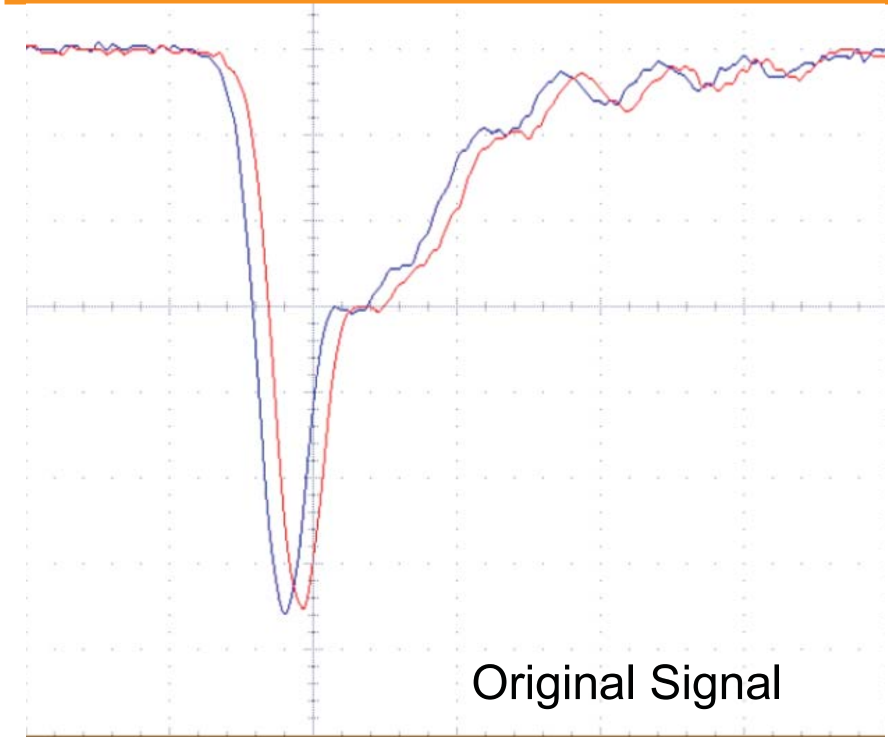


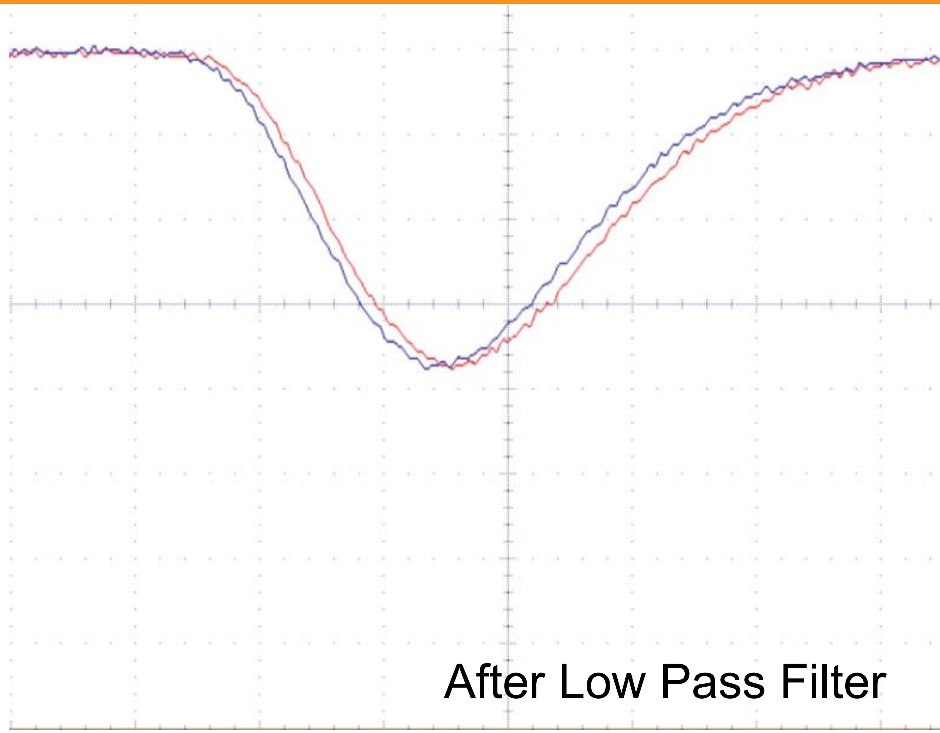
Digital timing

Is the sampling frequency a main limiting factor in timing measurements ?



Effects of Low Pass Filter [Nyquist]

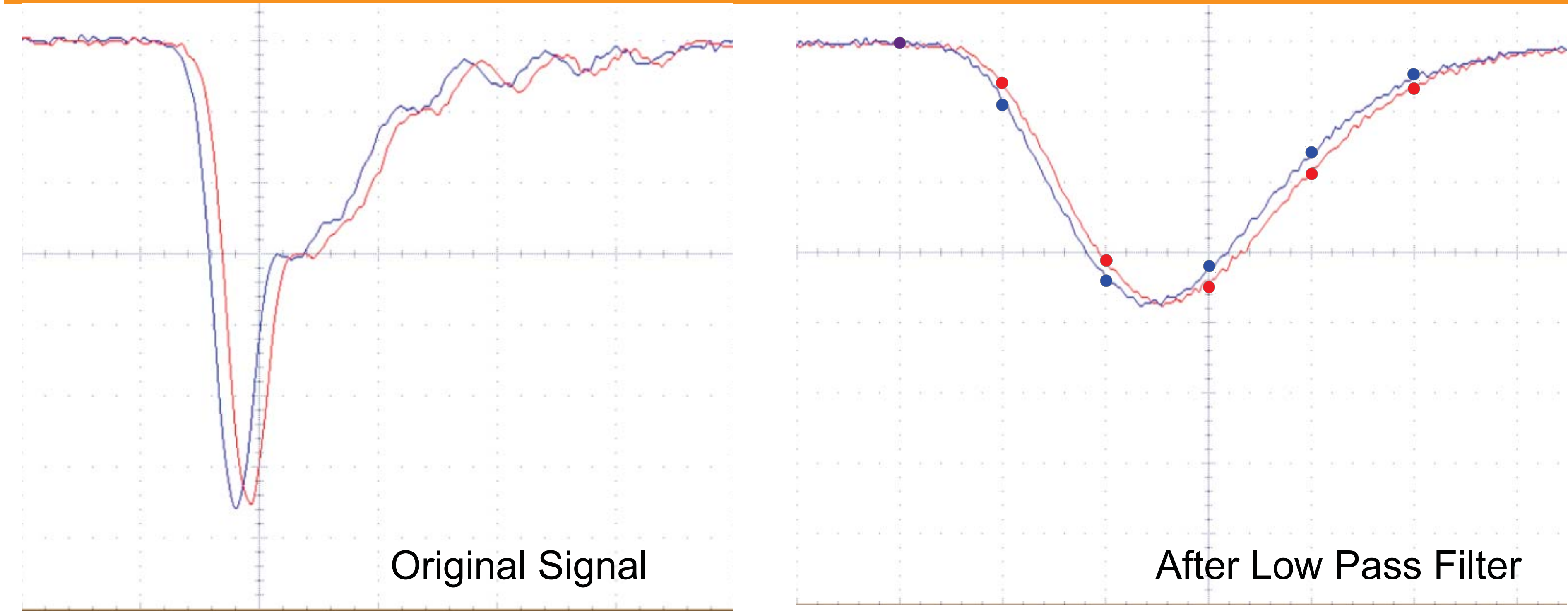




- Original signal is fast compared to the sampling period
- Time differences of <10ns still appear.
- 10ns/div on x-axis

S. Paulauskas (Univ. of Tenn)

Effects of Low Pass Filter [Nyquist]



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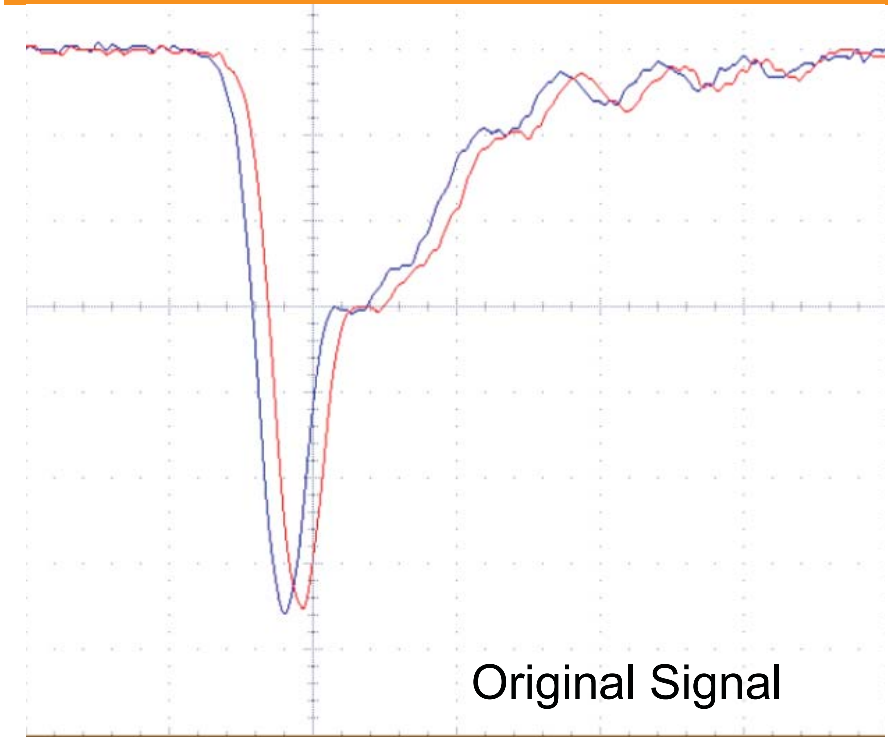

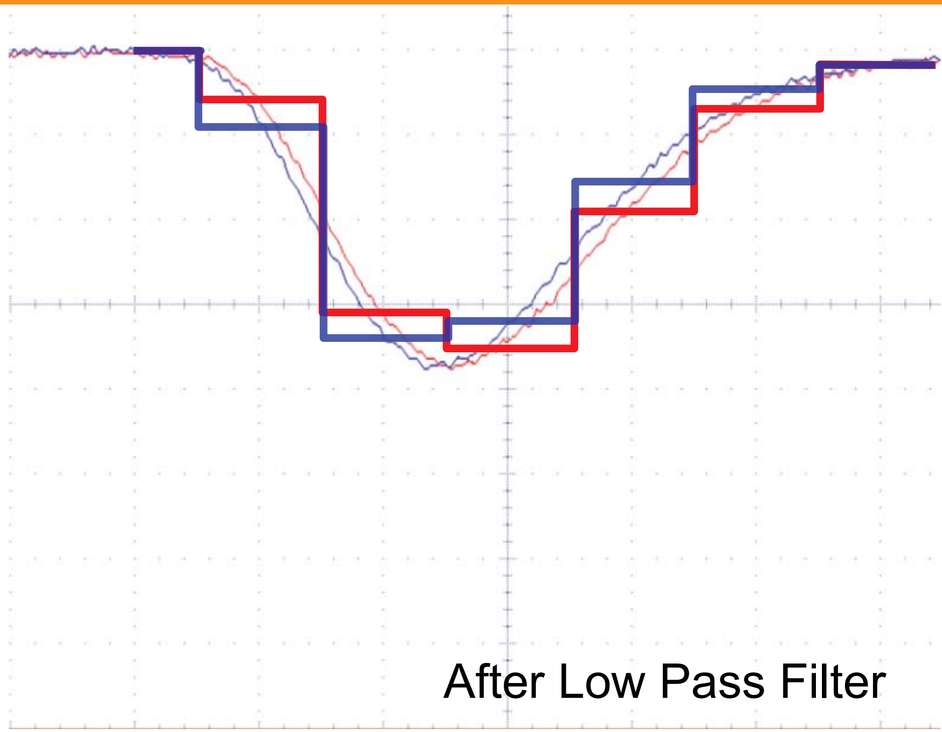

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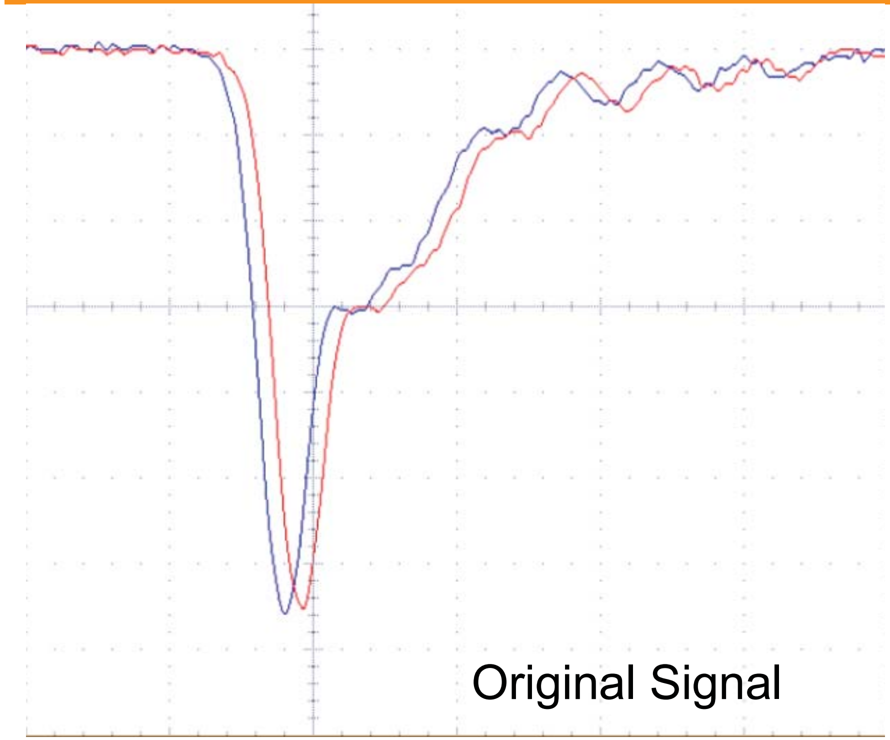
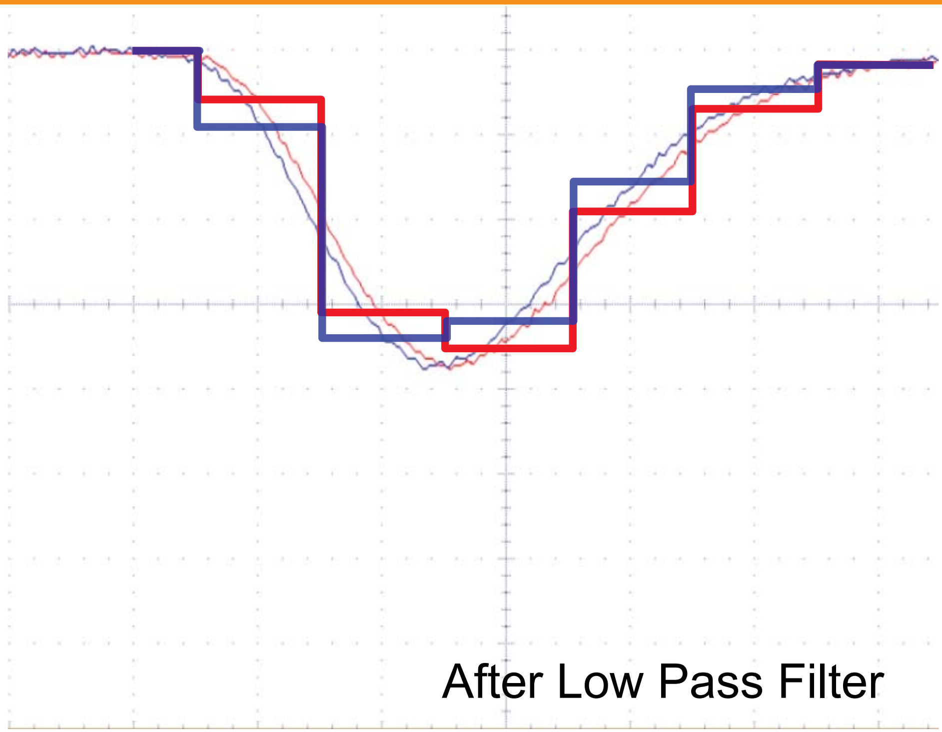
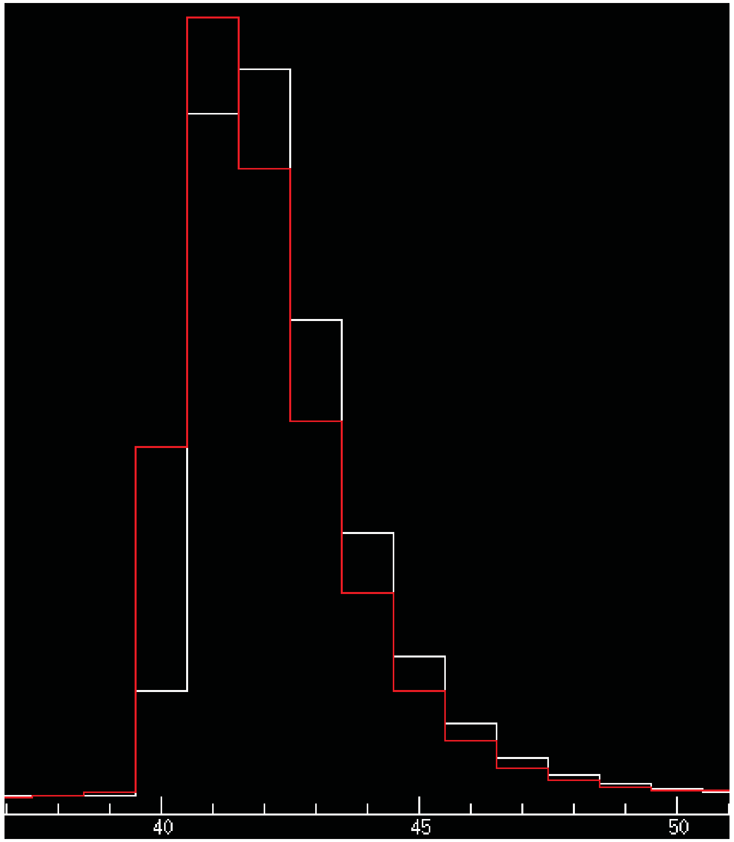




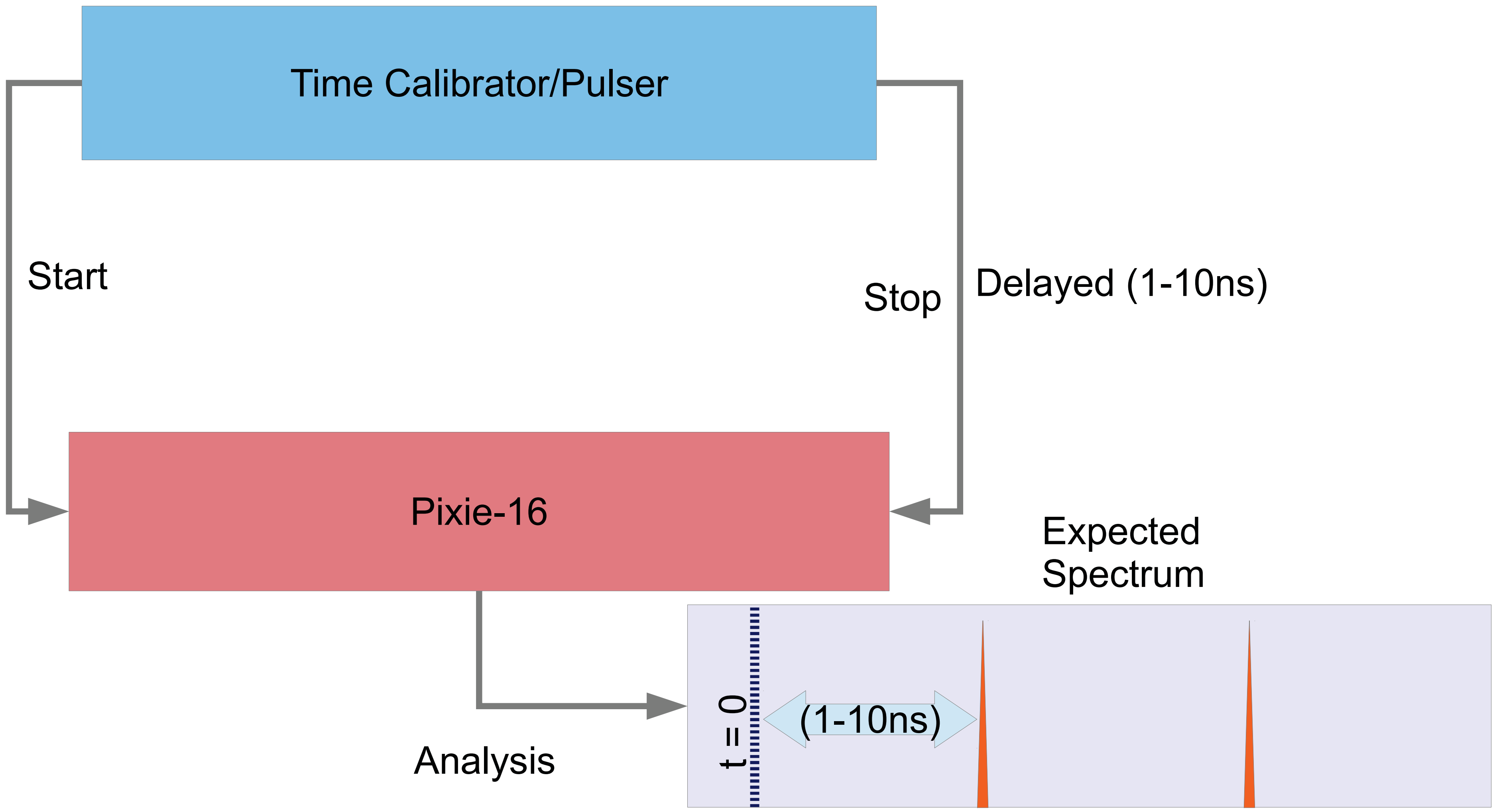
- Original signal is fast compared to the sampling period
- Time differences of <10ns still appear.
- 10ns/div on x-axis

Waveforms

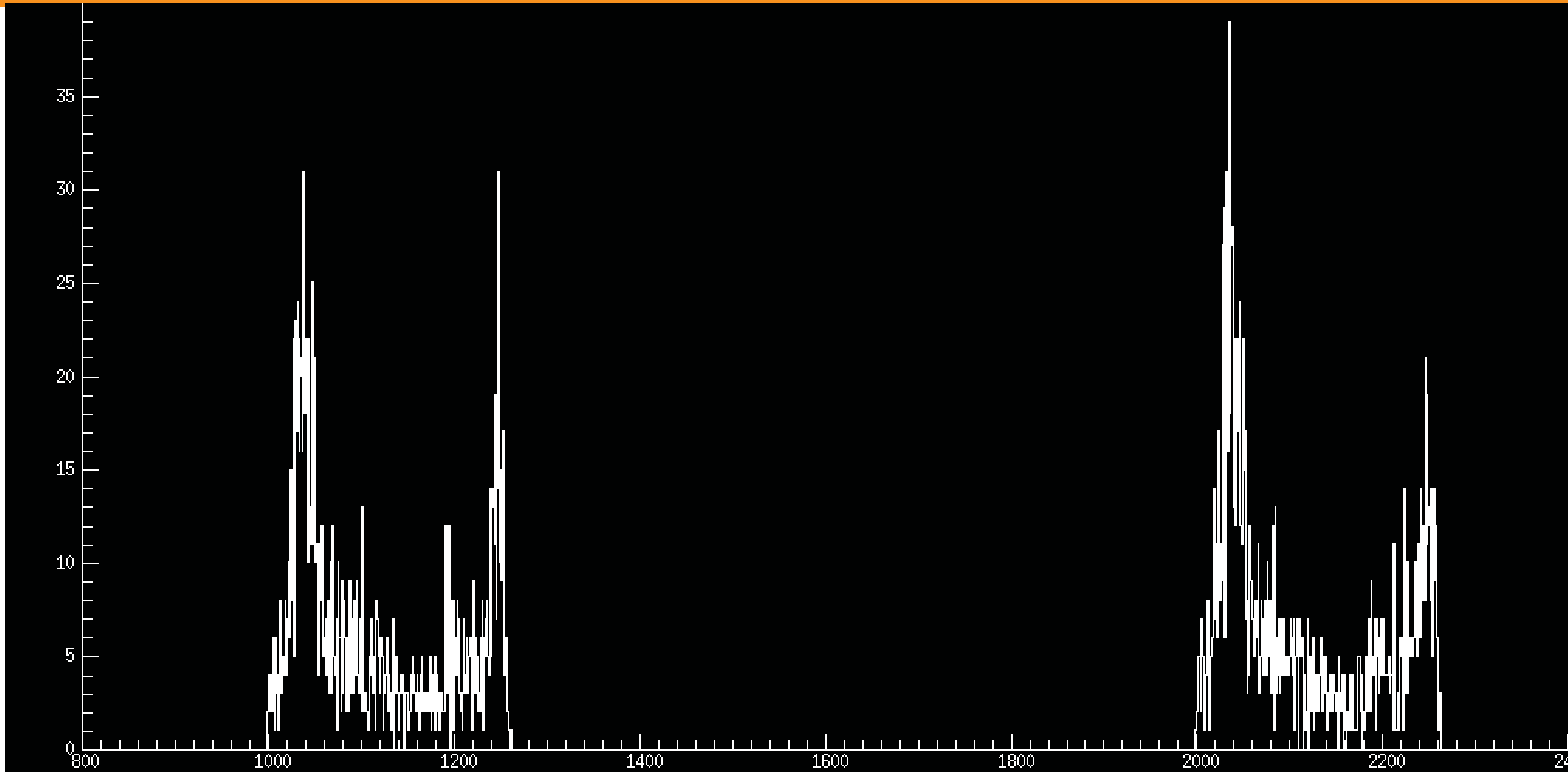
- Time in waveform referenced to internal clock
- Time information contained on leading edge through amplitude of sampling points.
- Can we extract time information that is less than the sampling frequency?



Timing: Experimental Setup



Timing: “Simplistic” digital CFD



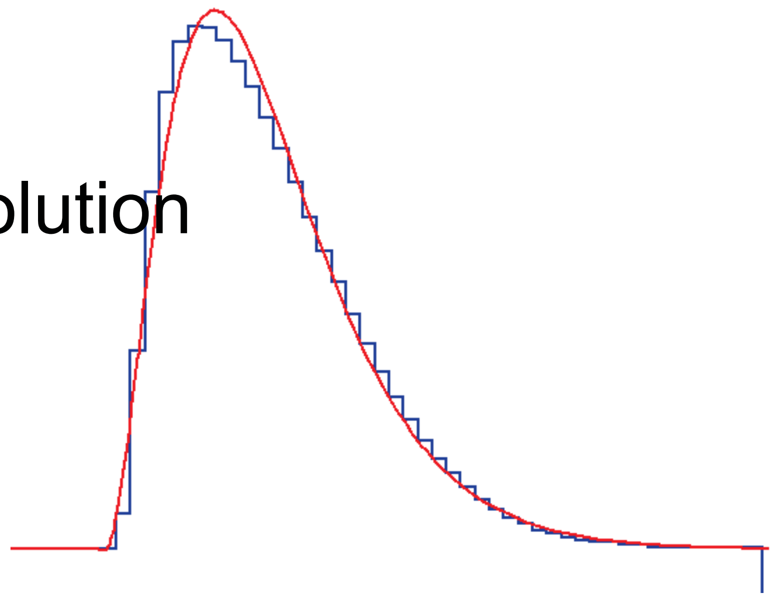
- Distance between the groups is 10ns
- Distance between peak pairs is ~2ns

Timing: Alternatives

- Pulse Fitting

$$f(t) = \alpha e^{-(t-t_0)/\lambda}\left(1 - e^{-(t-t_0)^2/\sigma}\right)$$

  - Fit the entire pulse
  - Can be time consuming
  - Produces excellent time resolution

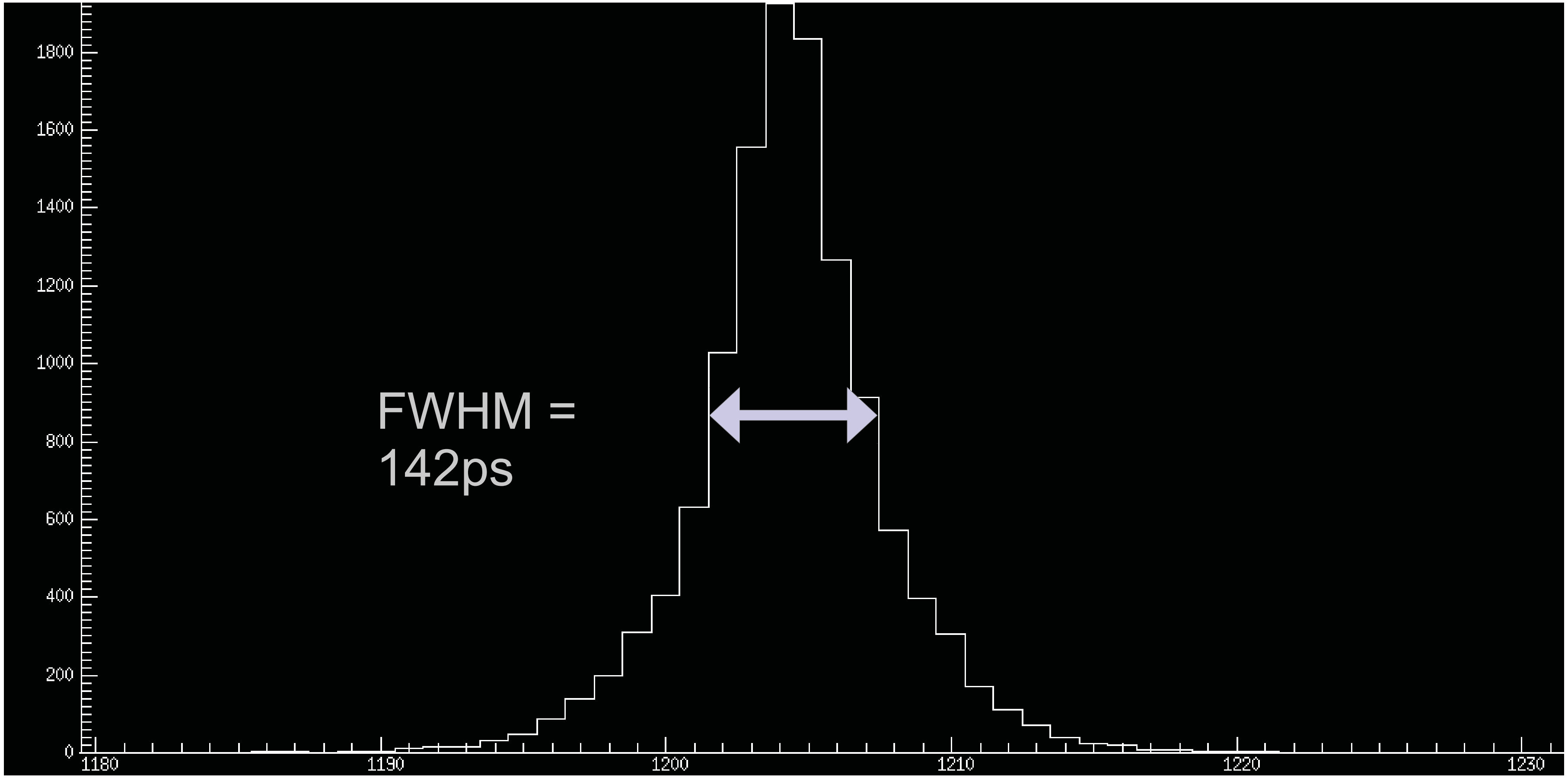


Single Point Analysis

  - Equation describes trace
  - Extremely fast analysis
  - Resolution comparable with fit

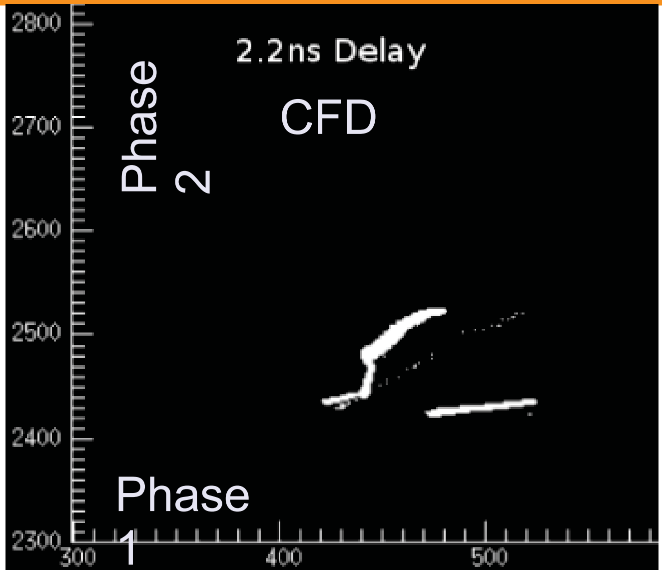
$$f(t) = \begin{cases} C_1 e^{-(t-t_0)^4 \sigma} & t < t_0 \\ C_2\left(e^{-(t-t_0)l_1} - \left(\frac{l_1}{l_2}\right) e^{-(t-t0-0.5)l_2}\right) & t \geq t_0 \end{cases}$$

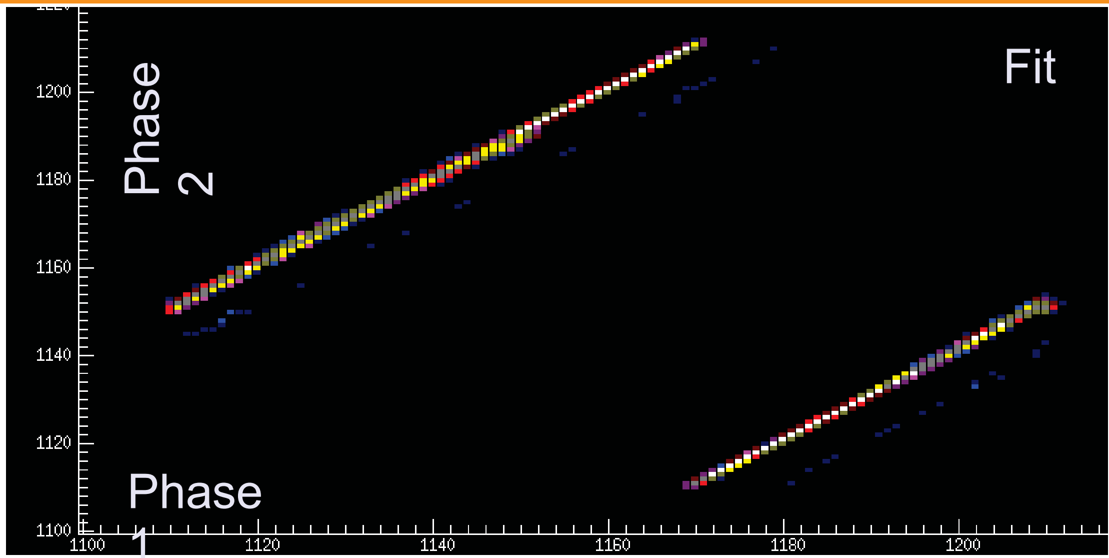
Timing : Single Point Analysis

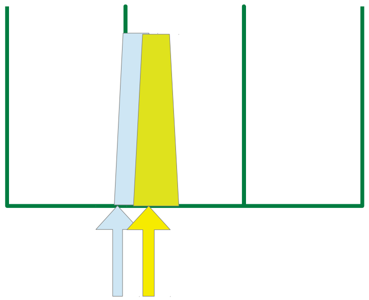


- We can measure with ~1% of the sampling interval.

Timing: Phase-Phase Diagram

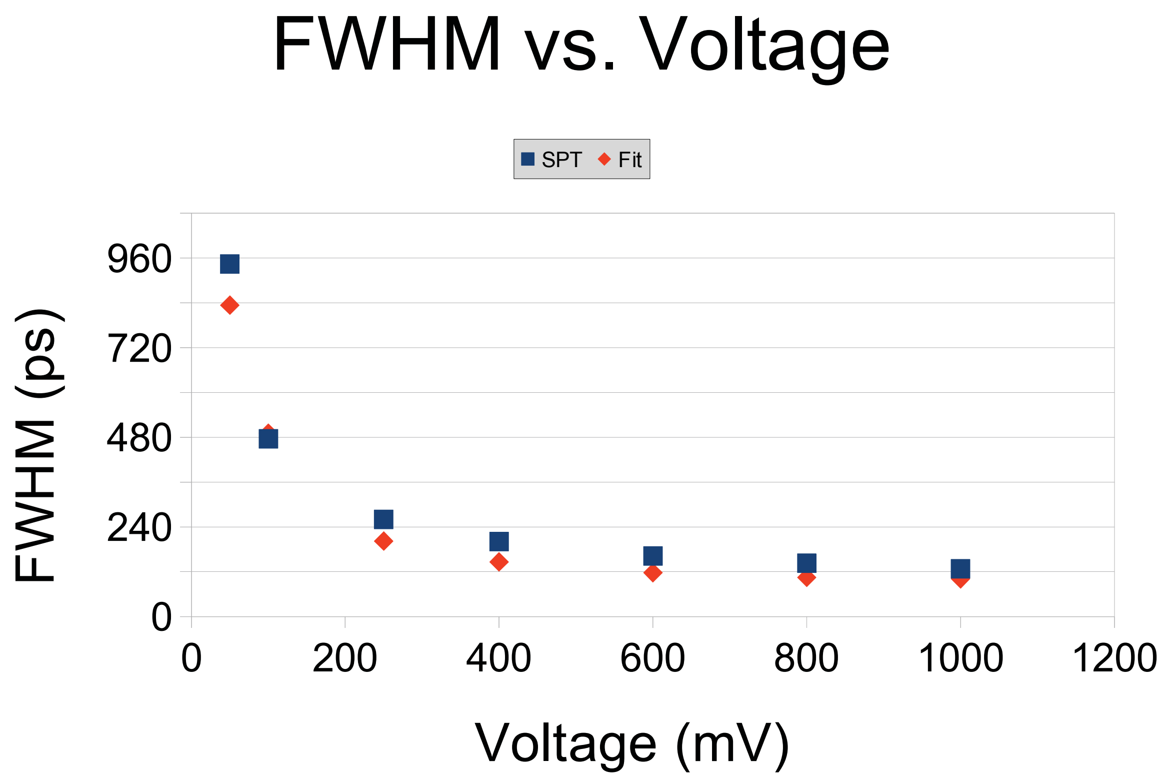






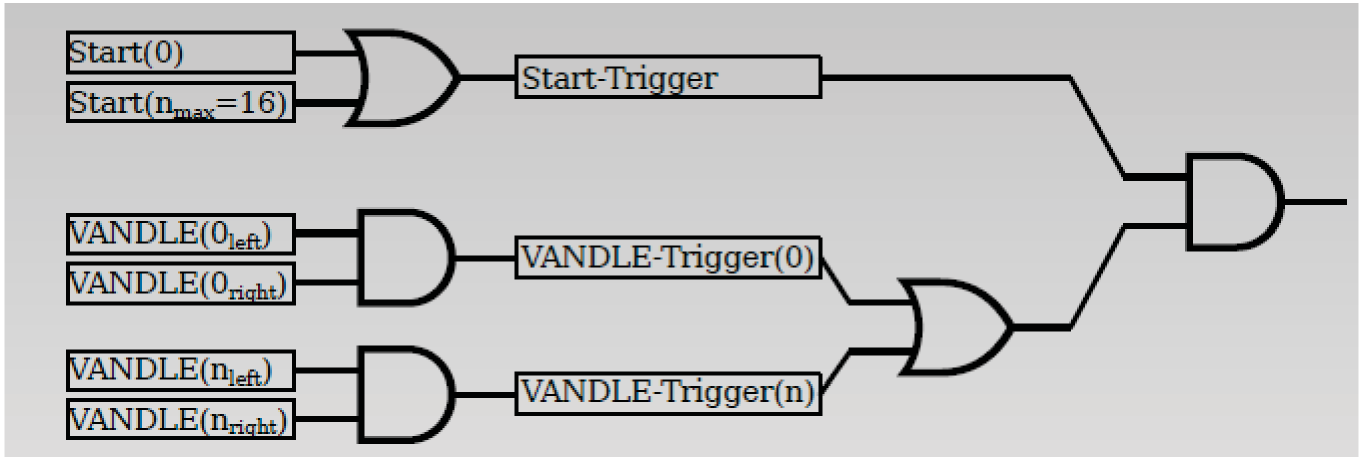
- Phase of first signal random with respect to 100Mhz clock
- Expect to see a straight line with a single slope

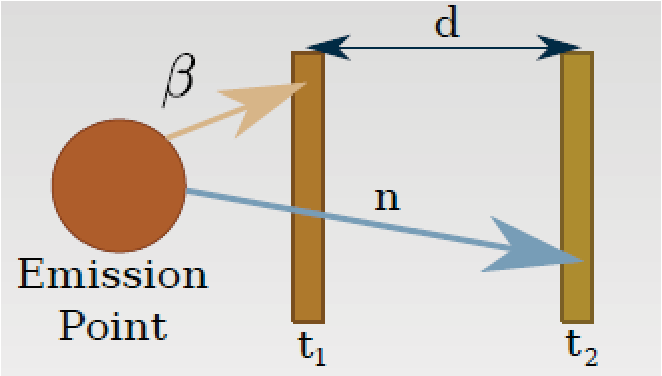
FWHM vs. Signal Voltage



- The two methods produce similar results.
- Degradation of resolution due to Pixie is minimal

Custom triggering scheme

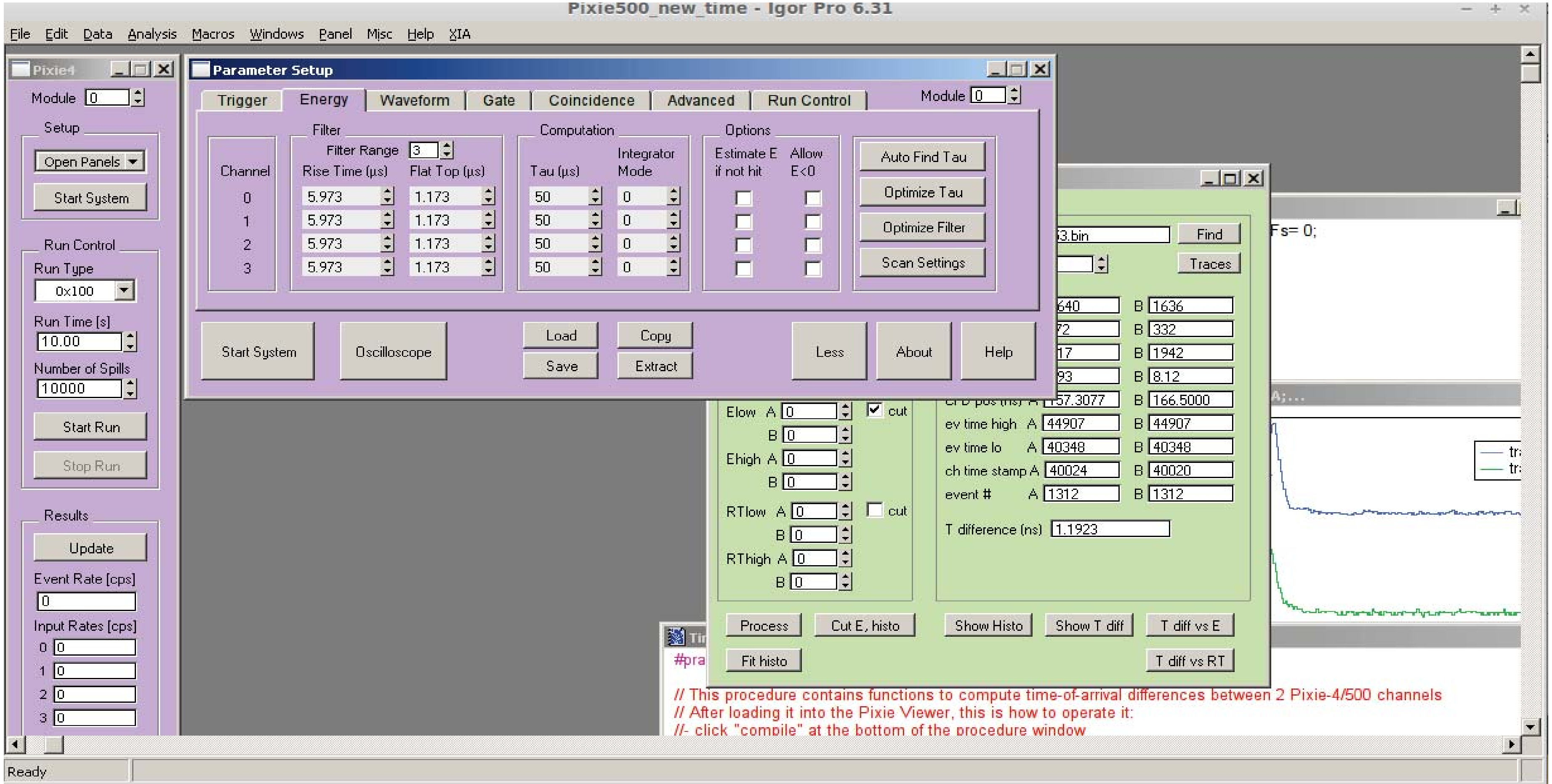




The PIXIE 500 board

500MSPS
16 us traces
MCA
PCI interface 70 Mbytes/s
16bit DSP
Offsets -2.5 V / +2.5 V

The PIXIE 500 board and IGOR GUI



The PIXIE 500 board and IGOR GUI