fast timing with slow scintillators

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what are the techniques?

- coincidence
- delayed coincidence
- time of flight

what are the applications?

- massive-gamma-ray detectors
- neutron time of flight

fast scintillators	**decay time**
plastic and liquid	1-2 ns
intermediate scintillators	
YAP(Ce), $LaCl_3$(Ce)	20 – 40 ns
slow scintillators	
NaI(Tl), CsI, BGO and $CdWO_4$	0.25 – 5µs

Time distribution of photon emission from scintillators

$$f'(t) = \frac{dQ(t)}{dt} = R\,?\,exp(-?t) \qquad \ldots(1)$$

$$f(t) = Q(t) = R(1-exp(-?t)) \qquad \ldots(2)$$

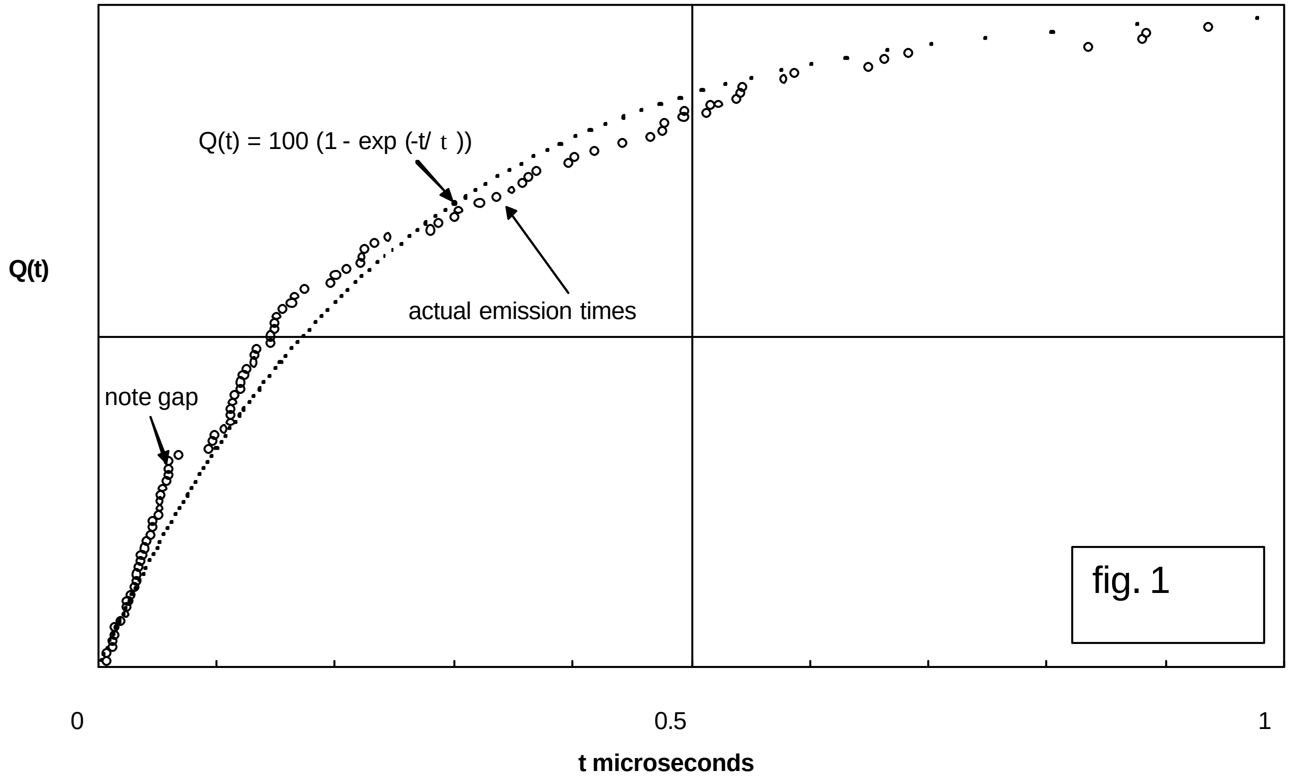


fig. 1

The probability distribution for the arrival time of the Q[th] photon, between *t* and *t* + *dt*, is a three-part process.

$$P_1(Q,R,?,t) = p_a .\, p_b .\, p_c$$

If *R* is fixed (no statistical fluctuation)

$$p_a = C(R,Q-1).\ \{ ?_{0}^{t} ?e^{-?t}dt \}^{Q-1}$$

$$p_b = C(R-(Q-1),1)\ ?e^{-?t}dt.$$

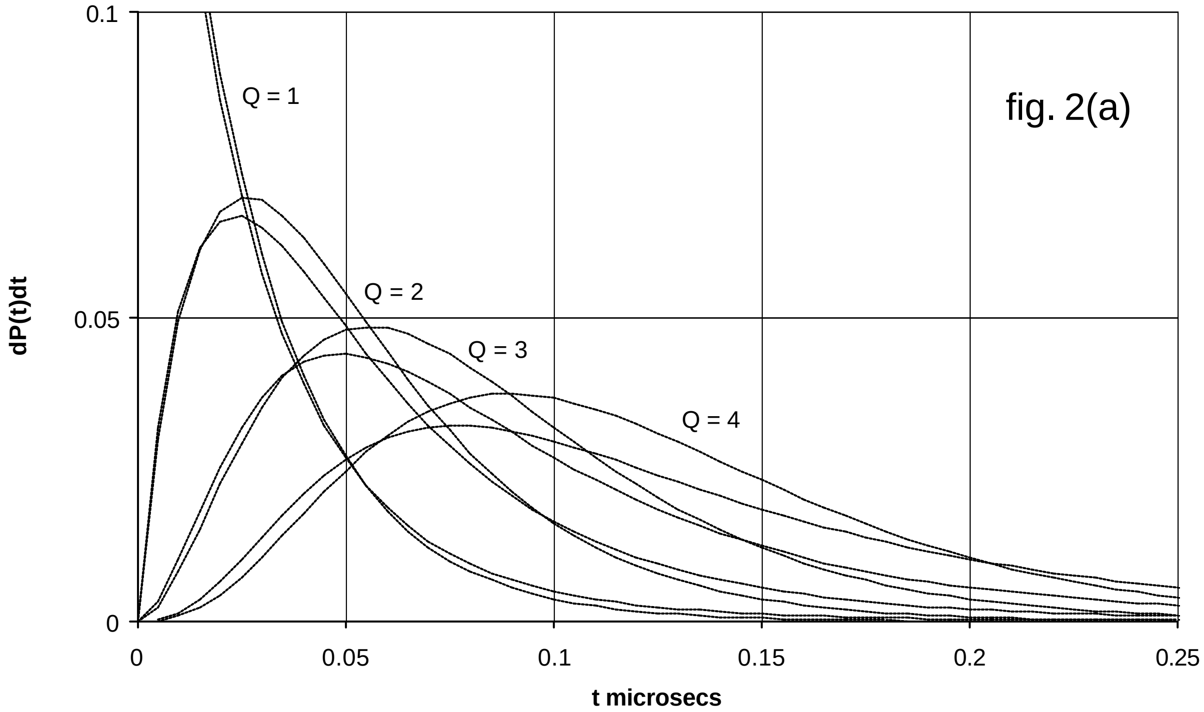
$$p_c = \{ ?_{t}^{8} ?e^{-?t}dt \}^{R-Q}$$

$$P_1(Q,R,?,t) = \frac{R!(1-e^{-?t})^{Q-1}}{(Q-1)!(R-(Q-1))!}\ (R-(Q-1))\ ?e^{-?t}dt\ (e^{-?t})^{R-Q} \qquad \ldots(3)$$

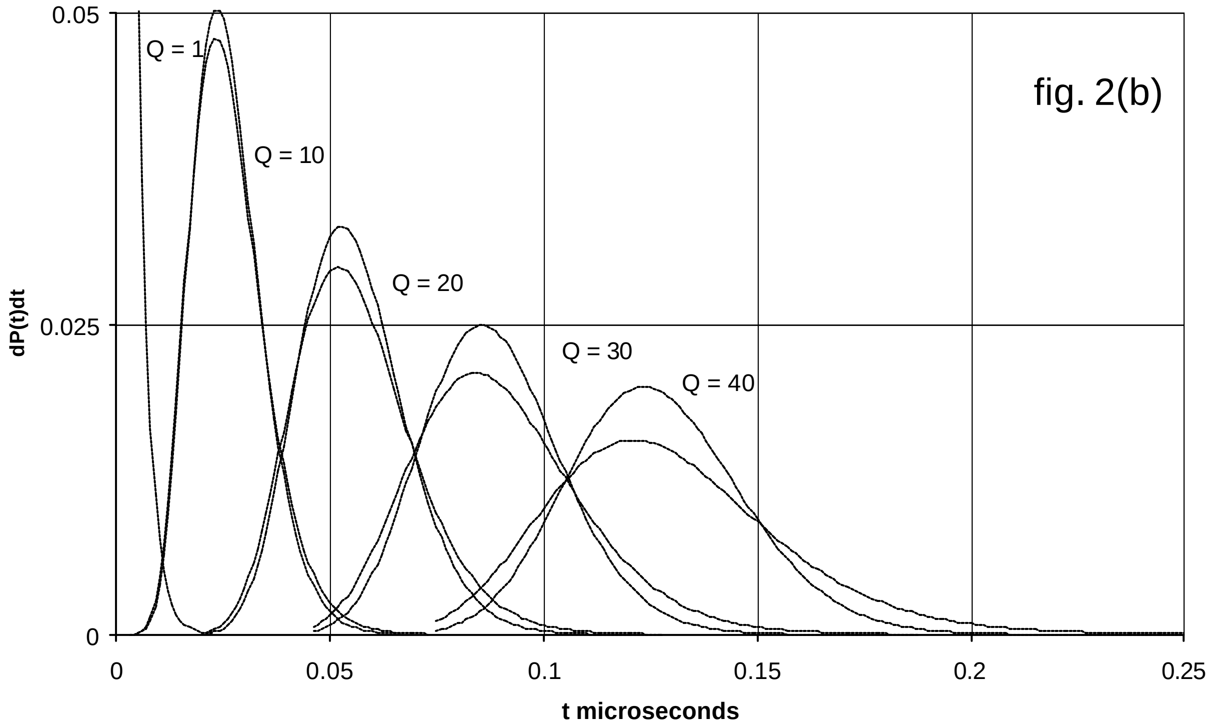
$$P_2(Q,R,?,t) = \frac{R^Q\ ?}{(Q-1)!}\ exp(-R(1 - e^{-?t})).(1 - e^{-?t})^{Q-1}\ e^{-?t}\ dt \qquad \ldots(4)$$

The time distribution for the arrival of the first photon is

$$P_2(1,R,?,t)\ \tilde{}\ \ R?\ exp(-(R+1)?t)\ dt \qquad \ldots(5)$$



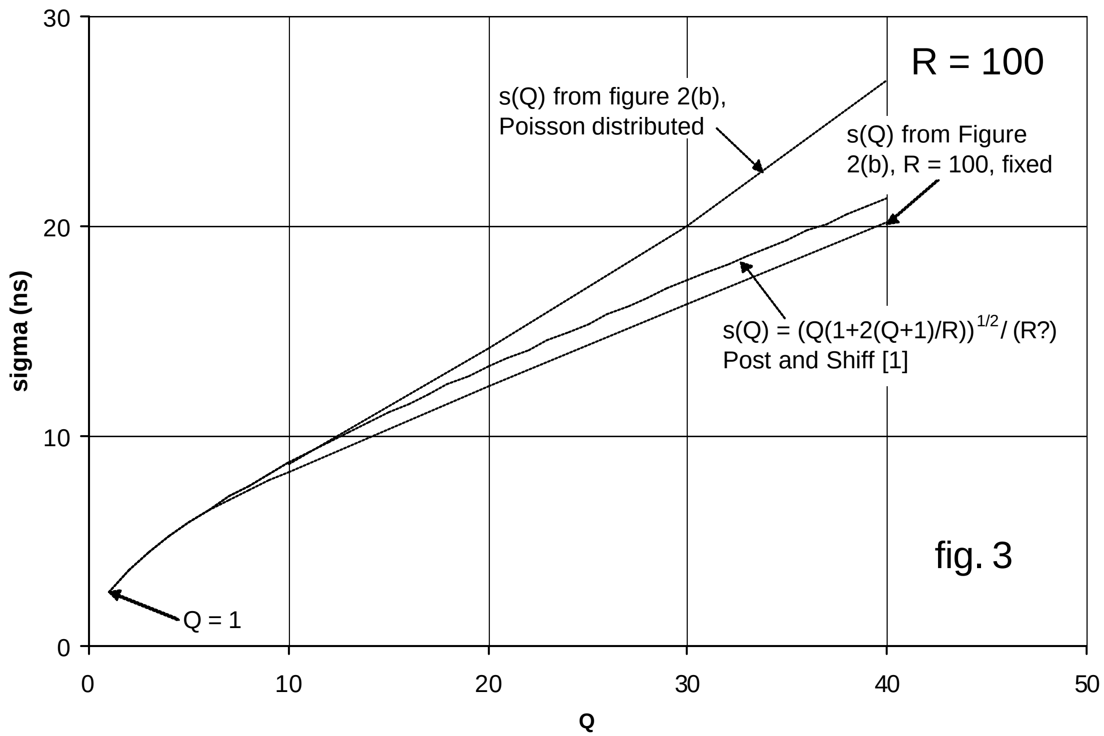
0.1
0.05
0
dP(t)dt
0
0.05
0.1
0.15
0.2
0.25
t microsecs
Q = 1
Q = 2
Q = 3
Q = 4
fig. 2(a)


0.05
0.025
0
dP(t)dt
Q = 1
Q = 10
Q = 20
Q = 30
Q = 40
fig. 2(b)
0
0.05
0.1
0.15
0.2
0.25
t microseconds

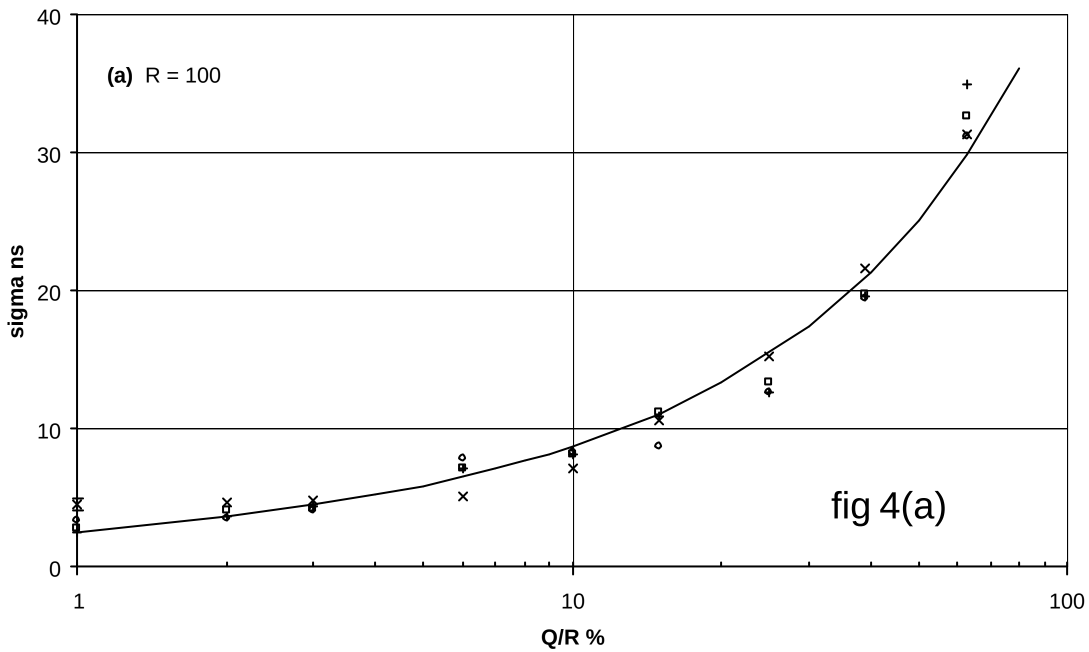
The variance of *P(Q,R,t,t)*

$$var_2(Q) = \frac{Q\,t^2}{R^2}\,(1 + 2(1+Q)/R + \ldots) \qquad \ldots(6)$$

subject to *R* large and *Q/R << 1*, whatever that means



The effect of photomultiplier transit time jitter, e_{ph}



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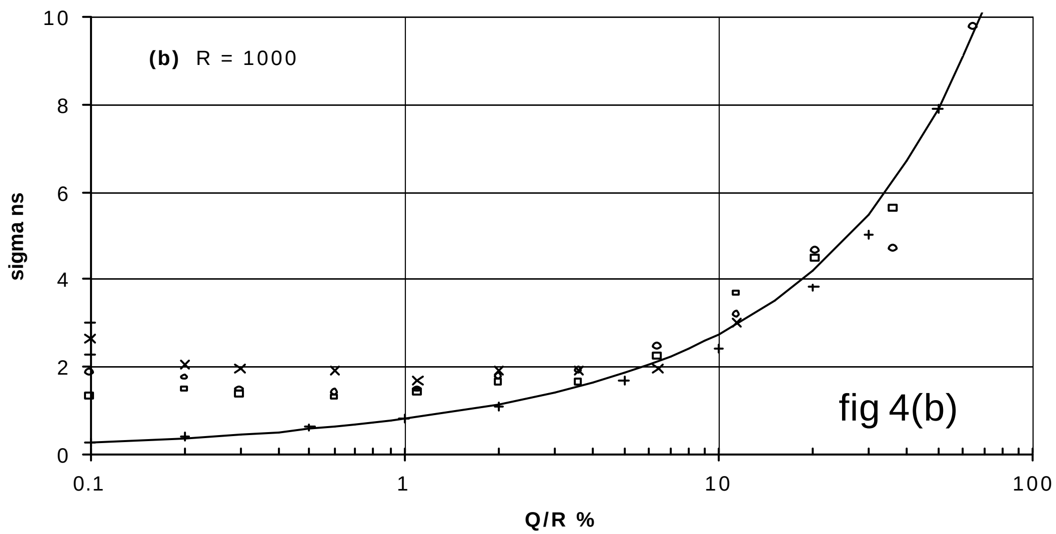
The effect of photomultiplier transit time jitter, e_{ph}



The effect of photomultiplier transit time jitter, e_{ph}

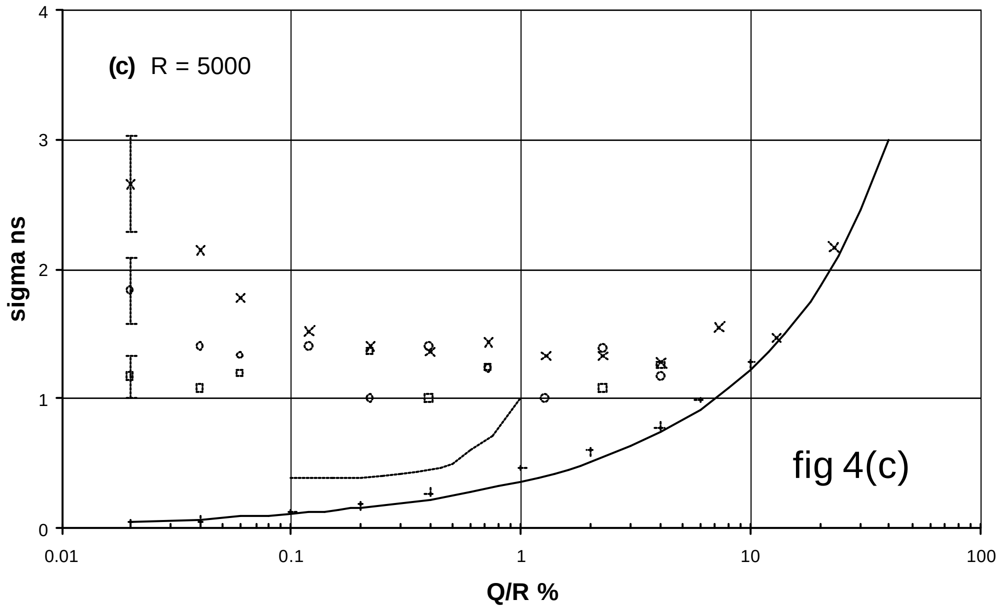


figure 4 *s(Q)* determined directly from *(4)*, **+** , with the predictions of *(6)*, solid line. The timing fidelity is impaired once transit time jitter is introduced. ?: e_{ph} *= 1 ns* ; ?: e_{ph} *= 2.5 ns*; x: e_{ph} *= 5 ns* . The sporadic error bars give an indication of the precision

The effect of noisy gain

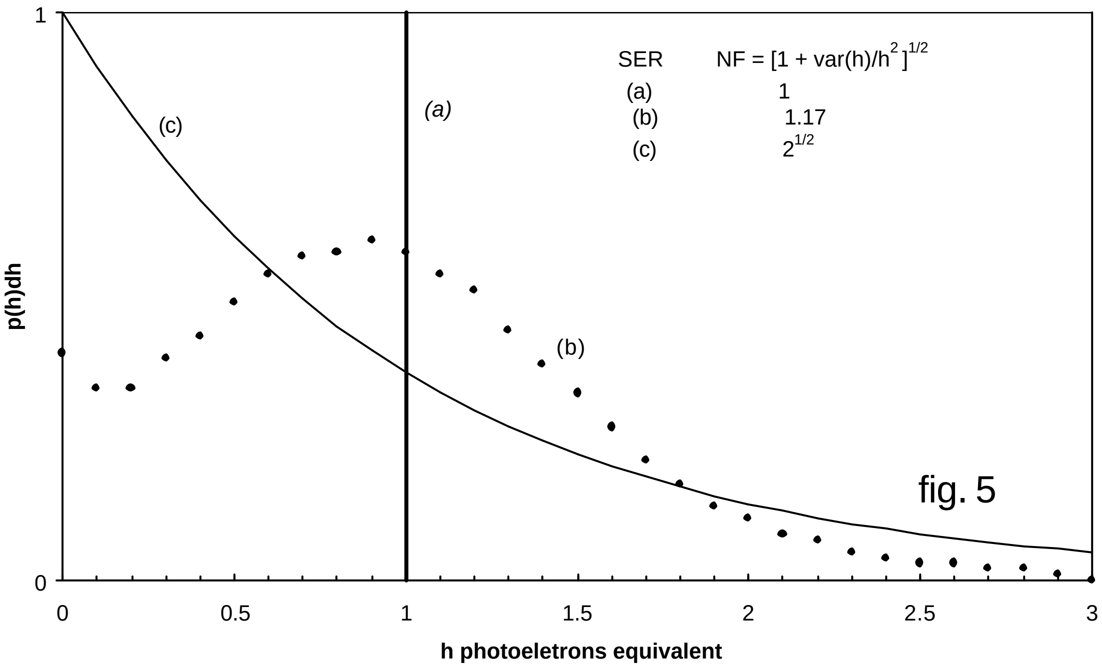


fig. 5

$NF = [\ 1 + e_A\ ]^{1/2}$ …(7)

where $e_A = var(h)/\langle h \rangle^2$, represents the gain dispersion, which can be calculated directed from the SER

The signal forming process at the anode

Each photoelectron produces a signal at the anode of

$$i(t) = q/t_s\ exp(-t/t_s) \qquad \ldots(7)$$

where q = e<g>

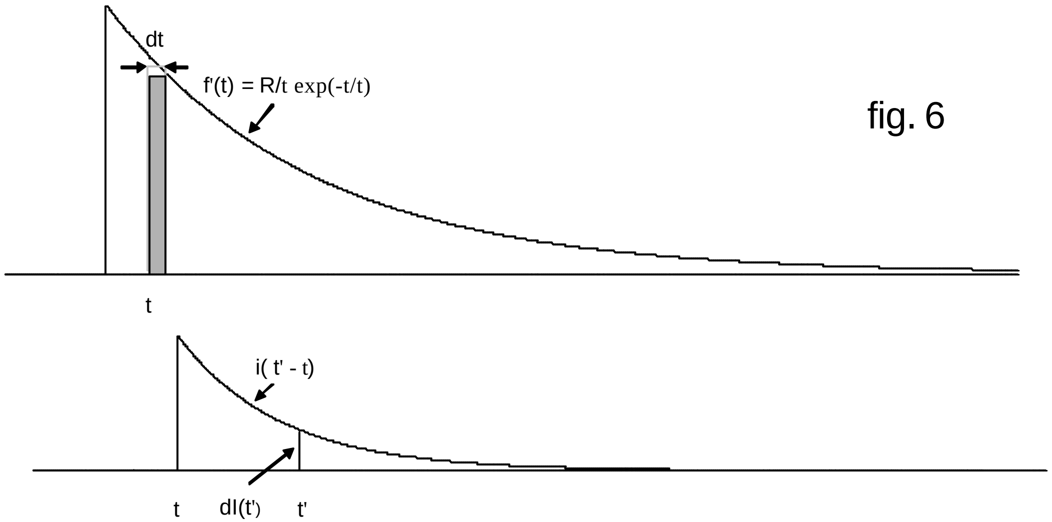
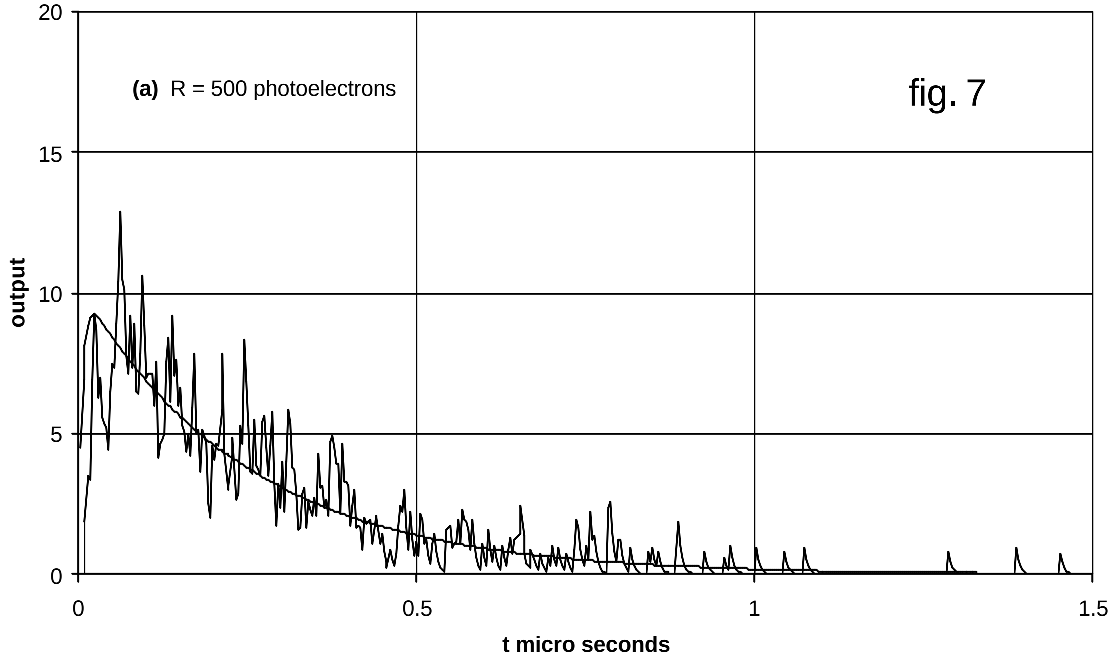


fig. 6

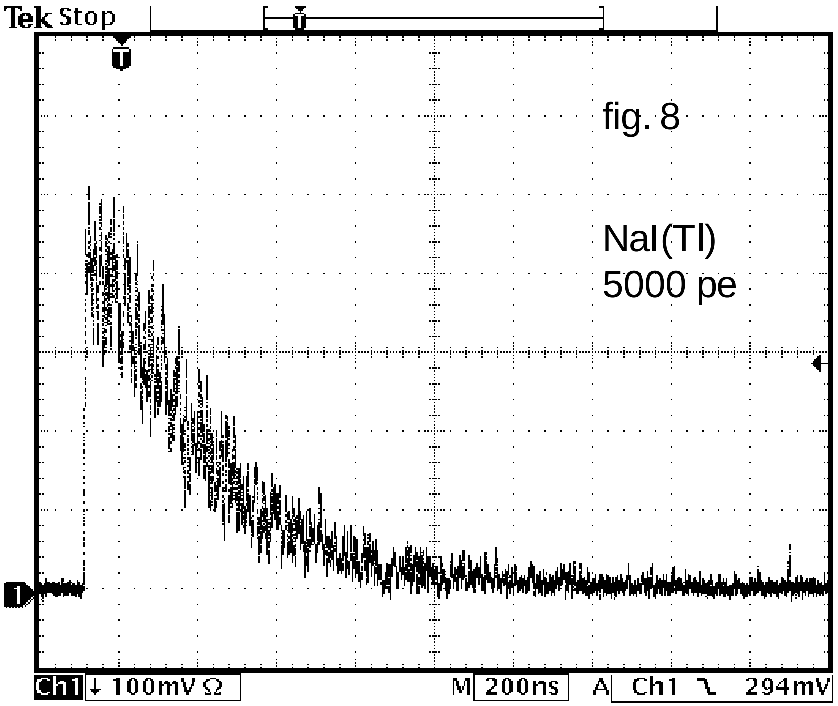
$$I(t') = \int_{0}^{t'} ?R?\ exp(-?t).\ q?_s\ exp(-?_s(t'-t))\ dt$$

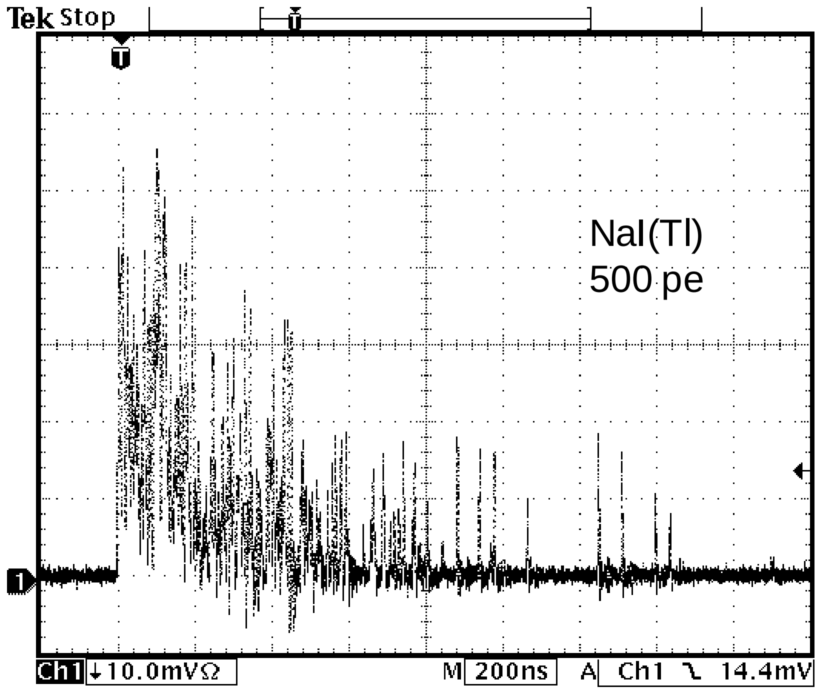
$$I(t) = \frac{Rq}{(t - t_s)} [exp(-t/t) - exp(-t/t_s)] \qquad \ldots(8)$$

Monte Carlo simulation of output pulses allowing for noisy gain and jitter e_{ph}



Actual NaI(Tl) pulses





The signal beyond the anode with time constant R′C′

$$I(t) = \frac{Rqt}{(t - t_s)} \frac{1}{t} \exp(-t/t) - \frac{Rqt_s}{(t - t_s)} \frac{1}{t_s} \exp(-t/t_s)$$

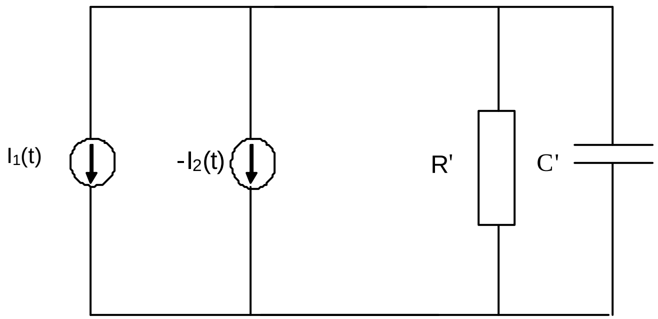


fig. 9

$$v_0(t) = \frac{R' q R}{(t - t_s)} \frac{t}{(t_0 - t)} (\exp(-t/t) - \exp(-t/t_0))$$

$$- \frac{R' q R}{(t - t_s)} \frac{t_s}{(t_0 - t_s)} (\exp(-t/t_s) - \exp(-t/t_0)) \quad \ldots(9)$$

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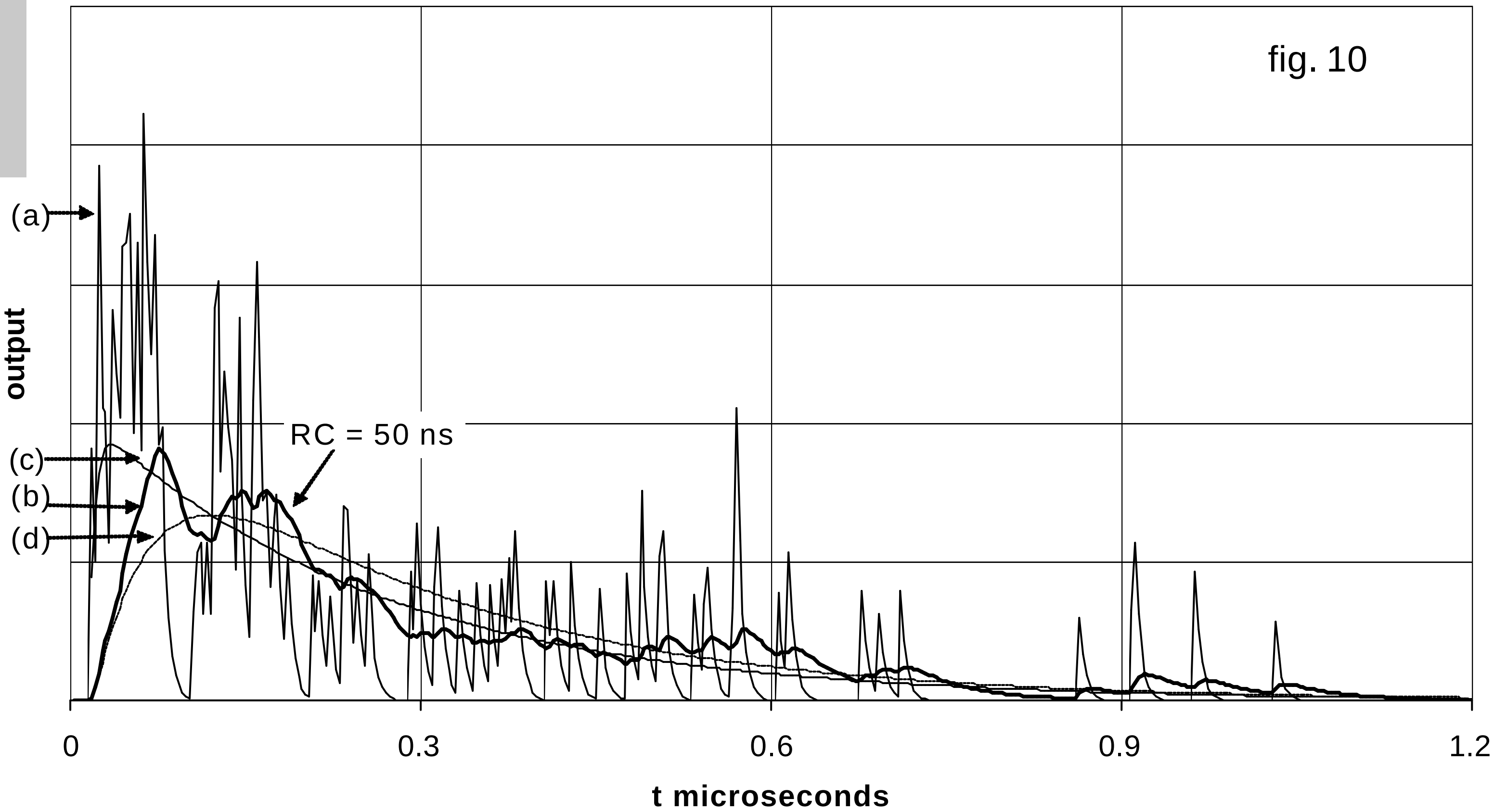


a) R = *100, t = 250 ns,* t_s *= 5 ns and* e_{ph} *= 5 ns.*
b) is the result of smoothing (a) with time-constant *R′C′.*
c) is the average of many repeat traces of type (a)
d) is a plot of equation *(9)* with *R′C′ = 50 ns.*

Note that the area under all curves is the same.

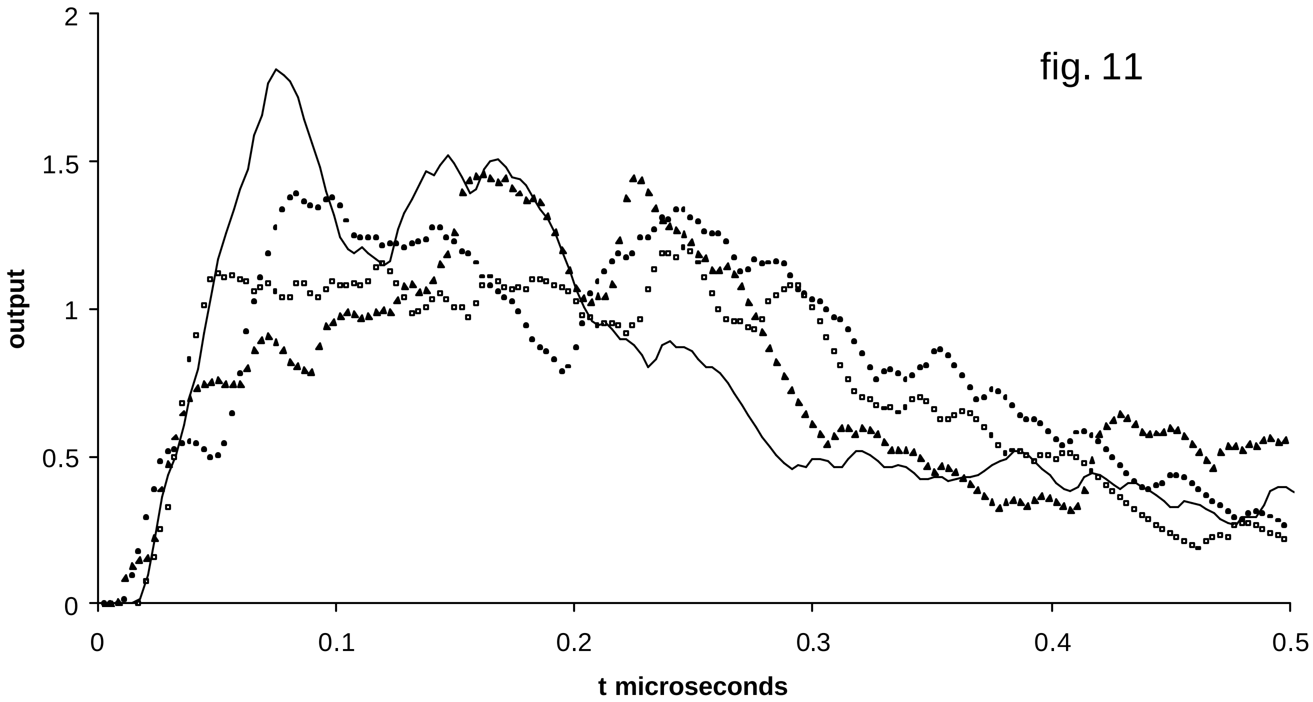


fig. 11
output
t microseconds
0
0.5
1
1.5
2
0
0.1
0.2
0.3
0.4
0.5

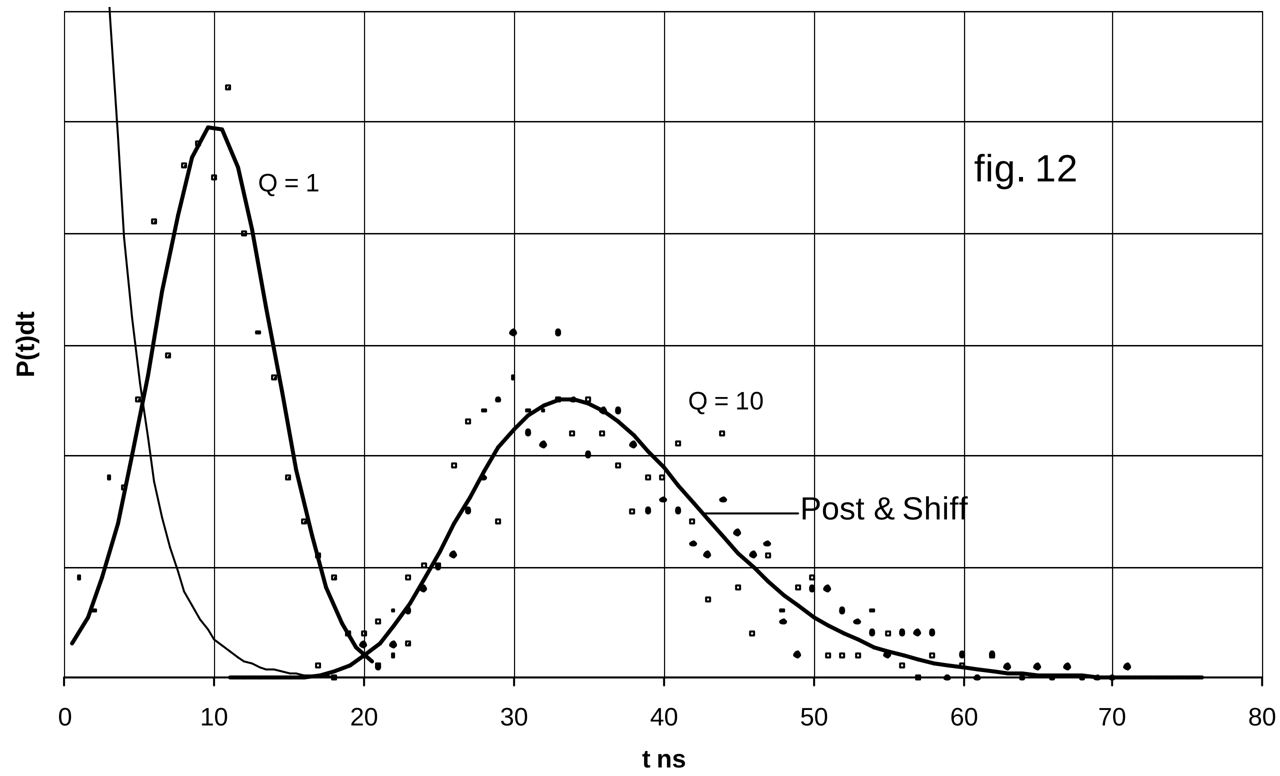
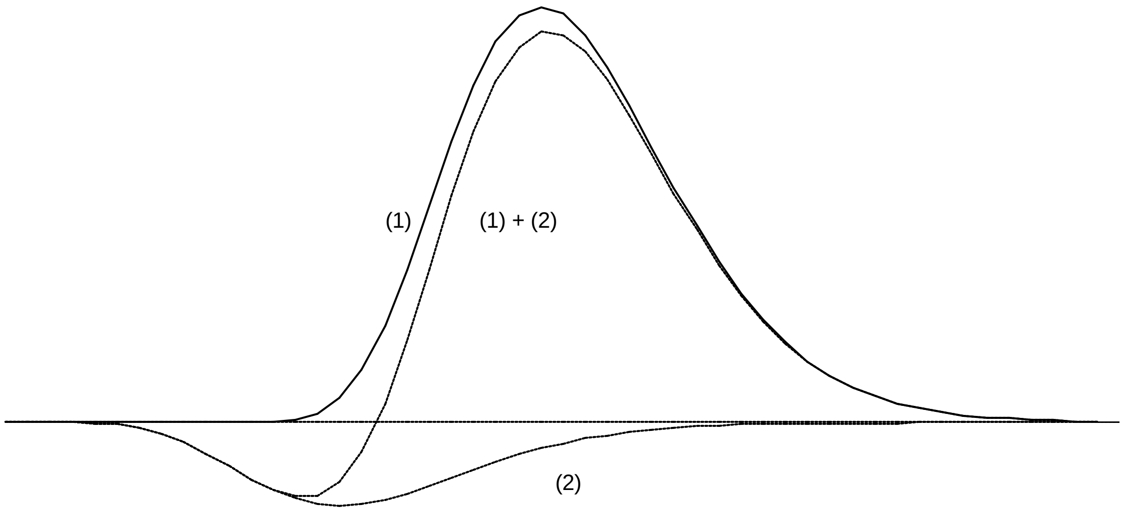
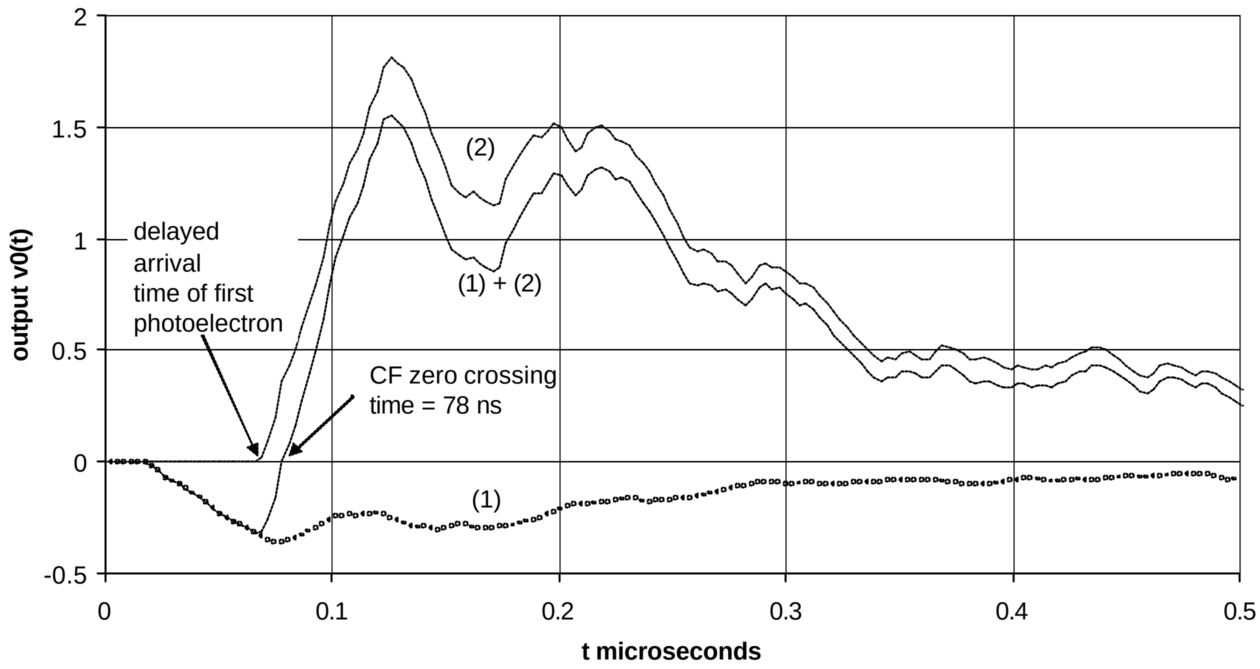


fig. 12
Q = 1
Q = 10
Post & Shiff
P(t)dt
t ns
0
10
20
30
40
50
60
70
80

Threshold and constant fraction discrimination




2
1.5
1
0.5
0
-0.5
0
0.1
0.2
0.3
0.4
0.5
output v0(t)
t microseconds
delayed
arrival
time of first
photoelectron
CF zero crossing
time = 78 ns
(2)
(1) + (2)
(1)

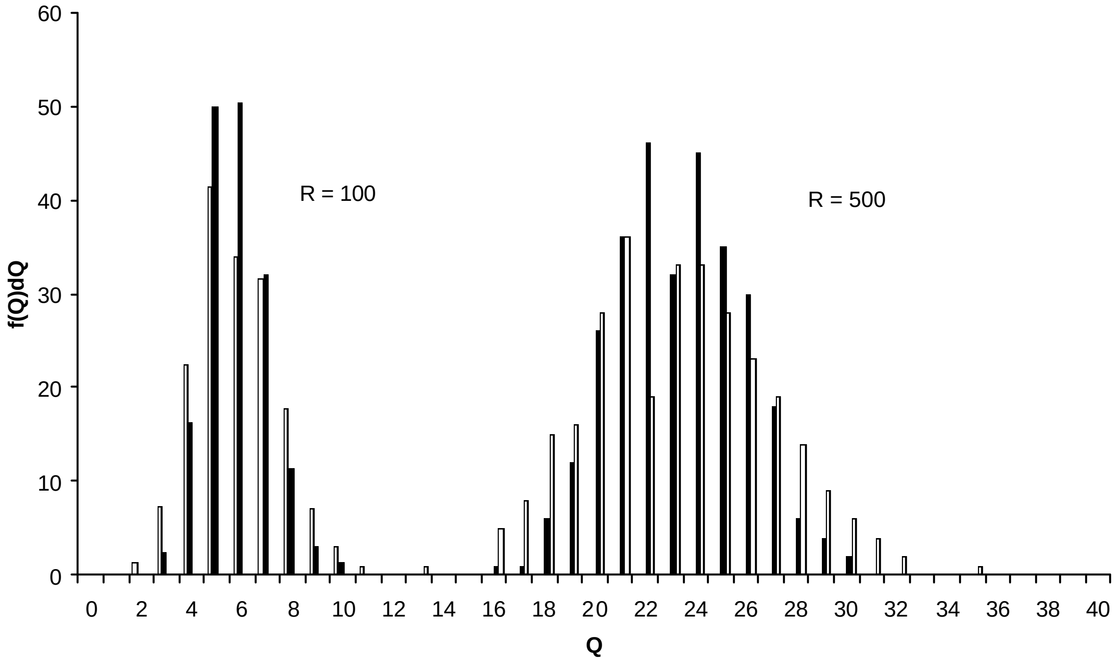
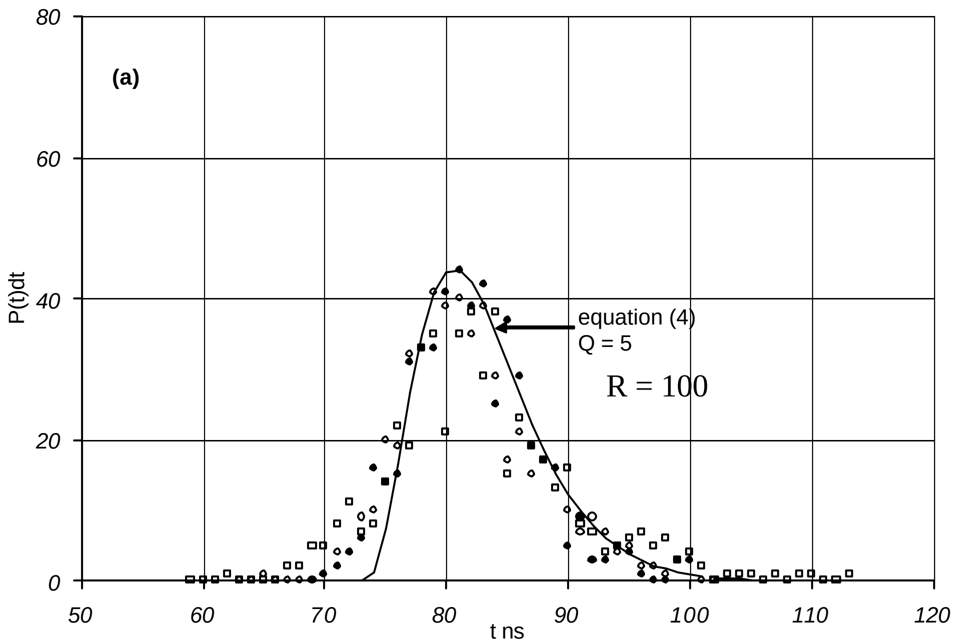


Figure 18 The number of photoelectrons, *Q*, required to trigger a CFD (20% , 50 ns delay). ¦ noiseless gain *(e_A = 0)* ; ? SER taken as Figure 7(b) *(e_A = 0.37)*



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Scintillator timing characteristics and other features

scintillator	?	t , ns	ph/keV	R/t (FOM)
BC418	1.03	1.4	8	5.7
BC400	1.03	2.4	8	3.3
$LaCl_3$	3.79	28	49	1.8
LuAP	8.30	18	20	1.1
YAP(Ce)	5.55	28	7	0.25
NaI(Tl)	3.67	250	40	0.16
CsI(Tl)	4.51	1000	60	0.06
BGO	7.13	300	8	0.03
$CdWO_4$	8.00	5000	14	0.003

Conclusions

1) fast timing with slow scintillators is possible if R/tau sufficiently large

2) although t >> e_{ph} pmt jitter is important at low Q values

3) a poor SER degrades timing under all conditions, directly as NF

4) smoothing is necessary to prevent multiple triggering

5) with CF technique smoothing under certain conditions does not degrade performance.

6) ultimately resort to experimentation with regard to smoothing, threshold, delay and trigger fraction

photomultiplier requirements

high QE
collection efficiency
SER
low jitter

catch the light

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solutions in light detection