DIRC R&D effort on the Multi-anode PMTs

(Log book #2)

J. Va’vra
New conditions:

1) Increase the ELANTEK amplifier gain from 10x to 50x.

2) This resulted in:
   a) increase of rise time from ~1.1ns to ~1.6ns (losing BW),
   b) increase of charge amplification by a factor of ~50.
   c) increase of a peak amplitude by a factor of ~2 only.

Gholam’s modification and measurement: 4.28.2002

Nominal 10x gain: Attempted 50x gain:

1) Amplifier output before the splitter: J.V., 4.29.2001
   1ns/div, 20mV/div.

2) Amplifier output after the splitter: J.V., 4.29.2001
   5ns/div, 20mV/div.
2) Signal after the splitter before the discriminator:

1ns/div, 10mV/div.  

Thresholds: 14.8 & 20.8 mV (1ns/div, 10mV/div)
Run 20 – Double thresholds, 50x amplifier:  

J.V., 5.2.2002

File: new_amp_37.dat, ~220000 triggers,  
62.5 μm dia. multi-mode fiber, PiLas laser diode at 5.2%, 10Hz internal trigger,  
choose the highest gain pad P2-2,  
New amplifier board for Elantec EL2075C, 50x charge gain (Gv~13x), which lowers a BW,  
Split the signal into two LeCroy 4413 discriminators, 14.8mV & 20.8mV thresholds,  
New high voltage PS made by Matsasuda,  
Probability of a hit ~ 2557/100000 ~ 2.6% only,  
22.371 psec/count TDC,  
H-8500 new 64-channel PMT with –1.0kV.

1. TDC spectra from each threshold:

a) Low threshold (14.8mV)  
b) High threshold (20.8mV)

![TDC spectra diagram]
2. TDC spectrum from a linear extrapolation to base line – do not require that both thresholds fire:

\[ t_0\text{-corrected} = t_1 - \left(\frac{(t_1-t_2)}{Vt_1-Vt_2}\right)\times Vt_1 \]

\[ \sigma \sim 131 \text{ ps} \quad \& \quad 309 \text{ ps} \]

3. Correlation between \( t_1 \) (TDC1) and \( t_2 \) (TDC2) – require that both thresholds fire:
4. TDC spectrum from a *nonlinear extrapolation* to base line:

\[ v(t) = a \left( t-t_0 \right) \exp\left[-(t_1-t_0)\tau\right] \]

\[ t_0 = t_2 \exp\left[(t_1-t_2)/\tau\right] - t_1 \left( Vt_2/Vt_1 \right) / \left[ \exp\left[(t_1-t_2)/\tau\right] - (Vt_2/Vt_1) \right], \]

where I have chosen \( \tau = 1.5 \text{ns} \).

\[ \sigma \approx 152 \text{ ps} \]

\[ & 234 \text{ ps} \]

(no correction)

5. Correlation between \( t_0 \) – non-linear and \( t_1 \) & \( t_2 \):

\[ \text{Fit: } G_1 + G_2 + a + bx + cx^2 \]
6. Use $t_2$ time to correct $t_1$ time to find the minimum:

$$t_{1\text{-corrected}} = t_1 - (-0.2012 t_2^2 + 8.8716 t_2 - 78.759 - 18.0)$$

7. Project the distribution to “t$_1$-corrected” axis:

- Incorrect manipulation with the correlated variables?

![Graph showing $t_1$ and $t_2$ distribution]
8. Bin data using a variable \( \text{diff} = t_2 - t_1 \), in each bin determine the mean linear extrapolation to base line, and then combine these to make the overall correction, which is non-linear:

a) Distribution of the diff variable:

![Distribution of diff variable](image)

<table>
<thead>
<tr>
<th>TD</th>
<th>108</th>
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<tbody>
<tr>
<td>Entries</td>
<td>3871</td>
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<tr>
<td>Mean</td>
<td>1.928</td>
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<tr>
<td>RMS</td>
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<tr>
<td>UDFLOW</td>
<td>0.003</td>
</tr>
<tr>
<td>OVEFLW</td>
<td>0.003</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>3871</td>
</tr>
</tbody>
</table>

\[ \text{diff} = t_2 - t_1 \text{ [ns]} \]

b) 1.7 ns < diff < 1.8 ns:

![Distribution of t0 linear](image)

<table>
<thead>
<tr>
<th>TD</th>
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<tbody>
<tr>
<td>Entries</td>
<td>614</td>
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<tr>
<td>Mean</td>
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<td>RMS</td>
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<td>9.000</td>
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<td>ALLCHAN</td>
<td>605.0</td>
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</table>

\[ \chi^2/\text{ndf} \quad 16.71 / 6 \]

P1 = 1.106
P2 = 13.92
P3 = 0.1352
P4 = 1.343
P5 = 0.1472
P6 = 0.1899
b) $1.8 \text{ ns} < \text{diff} < 1.9 \text{ ns}$:

![Graph showing t₀-linear [ns] distribution](image)

<table>
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<td>Entries</td>
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<td>1470</td>
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<td>$\chi^2$/ndf</td>
<td>5.254 / 10</td>
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<tr>
<td>P1</td>
<td>242.0</td>
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<tr>
<td>P2</td>
<td>13.86</td>
</tr>
<tr>
<td>P3</td>
<td>0.1527</td>
</tr>
<tr>
<td>P4</td>
<td>-71.24</td>
</tr>
<tr>
<td>P5</td>
<td>-0.1524E-01</td>
</tr>
<tr>
<td>P6</td>
<td>0.4194</td>
</tr>
</tbody>
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\[ t_0 – \text{linear [ns]} \]

---

c) $1.9 \text{ ns} < \text{diff} < 2.0 \text{ ns}$:

![Graph showing t₀-linear [ns] distribution](image)

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<tr>
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<td>$\chi^2$/ndf</td>
<td>6.879 / 8</td>
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<tr>
<td>P1</td>
<td>128.8</td>
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<tr>
<td>P2</td>
<td>13.74</td>
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<tr>
<td>P3</td>
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<td>P4</td>
<td>-19.56</td>
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<tr>
<td>P5</td>
<td>0.3364E-01</td>
</tr>
<tr>
<td>P6</td>
<td>0.1186</td>
</tr>
</tbody>
</table>

\[ t_0 – \text{linear [ns]} \]
c) 2.0 ns < diff < 2.1 ns:

\[
t_{0}\text{-linear [ns]}
\]

\[
\begin{array}{|c|}
\hline
TD & 112 \\
Entries & 364 \\
Mean & 13.69 \\
RMS & 0.2552 \\
UDFLW & 1.000 \\
OVRFLW & 0.000 \\
ALLCHAN & 383.0 \\
\hline
\end{array}
\]

\[
\chi^{2}/\text{ndf} & 8.164 / 8 \\
P1 & 57.26 \\
P2 & 13.56 \\
P3 & 0.1540 \\
P4 & -12.87 \\
P5 & 0.6058E-01 \\
P6 & 0.7685E-01 \\
\]


d) 2.1 ns < diff < 2.2 ns:

\[
t_{0}\text{-linear [ns]}
\]

\[
\begin{array}{|c|}
\hline
TD & 113 \\
Entries & 244 \\
Mean & 13.43 \\
RMS & 0.3197 \\
UDFLW & 0.000 \\
OVRFLW & 5.000 \\
ALLCHAN & 239.0 \\
\hline
\end{array}
\]

\[
\chi^{2}/\text{ndf} & 6.735 / 8 \\
P1 & 36.36 \\
P2 & 13.35 \\
P3 & 0.1653 \\
P4 & -14.53 \\
P5 & 0.1341E-01 \\
P6 & 0.8786E-01 \\
\]
e) 2.2 ns < diff < 2.3 ns:

\[
\begin{array}{|c|}
\hline
\text{ID} & 114 \\
\text{Entries} & 115 \\
\text{Mean} & 13.30 \\
\text{RMS} & 0.4067 \\
\text{UDFLW} & 0.000 \\
\text{OVFLW} & 1.000 \\
\text{ALLCHAN} & 114.0 \\
\hline
\end{array}
\]

\[\chi^2/\text{ndf} = 4.409 / 6\]

\[
\begin{array}{|c|}
\hline
\text{P1} & 15.20 \\
\text{P2} & 13.16 \\
\text{P3} & 0.2197 \\
\text{P4} & -28.40 \\
\text{P5} & -0.3451E-01 \\
\text{P6} & 0.1616 \\
\hline
\end{array}
\]

f) 2.3 ns < diff < 2.4 ns:

\[
\begin{array}{|c|}
\hline
\text{ID} & 115 \\
\text{Entries} & 105 \\
\text{Mean} & 13.03 \\
\text{RMS} & 0.4075 \\
\text{UDFLW} & 0.000 \\
\text{OVFLW} & 0.000 \\
\text{ALLCHAN} & 105.0 \\
\hline
\end{array}
\]

\[\chi^2/\text{ndf} = 13.14 / 8\]

\[
\begin{array}{|c|}
\hline
\text{P1} & 12.11 \\
\text{P2} & 12.91 \\
\text{P3} & 0.1884 \\
\text{P4} & -4.455 \\
\text{P5} & 0.1112E-01 \\
\text{P6} & 0.2935E-01 \\
\hline
\end{array}
\]
g) Corrected time: \( t_0\text{-linear} = f(\text{diff}) \):

\[
y = -1.619x^2 + 4.9167x + 10.29
\]

h) A final distribution of “\( t_0 - t_0\text{-linear(diff)} +14.0 \)” variable:

\( \sigma \sim 150 \text{ ps} \) & \( 249 \text{ ps} \) (with correction)
8. Bin data using a variable \( \text{diff} = t_2 - t_1 \), in each bin determine the mean non-linear extrapolation to base line, and then combine these to make the overall correction, which is non-linear:

a) Distribution of the diff variable:

![Histogram of diff variable with distribution details.]

<table>
<thead>
<tr>
<th>ID</th>
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</thead>
<tbody>
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<td>0.003</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>3871</td>
</tr>
</tbody>
</table>

\( \text{diff} = t_2 - t_1 \) [ns]

b) 1.7 ns < diff < 1.8 ns:

![Histogram of t0–nonlinear [ns] with distribution details.]

<table>
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<tbody>
<tr>
<td>Entries</td>
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<tr>
<td>Mean</td>
<td>17.95</td>
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<tr>
<td>RMS</td>
<td>0.4326</td>
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<td>UDFLOW</td>
<td>0.000</td>
</tr>
<tr>
<td>OVERFLOW</td>
<td>6.000</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>608.0</td>
</tr>
</tbody>
</table>

\( \chi^2 / \text{ncf} \) 15.39 / 9

| F1 | 110.3 |
| F2 | 17.82 |
| F3 | 0.1388 |
| F4 | -1.122 |
| F5 | 0.2604E-01 |
| F6 | 0.4095E-01 |
b) 1.8 ns < diff < 1.9 ns:

![Graph showing t₀–nonlinear [ns] distribution for 1.8 ns < diff < 1.9 ns]

- TD: 111
- Entries: 1474
- Mean: 17.99
- RMS: 0.3575
- UNDERW: 0.000
- OVERW: 7.000
- ALLCHAN: 1467
- $\chi^2$/rdf: 17.33 / 10
- P1: 228.7
- P2: 17.91
- P3: 0.1554
- P4: -126.6
- P5: -0.1766E-01
- P6: 0.4319

\[t_0-\text{nonlinear [ns]}\]


c) 1.9 ns < diff < 2.0 ns:

![Graph showing t₀–nonlinear [ns] distribution for 1.9 ns < diff < 2.0 ns]

- TD: 112
- Entries: 857
- Mean: 18.14
- RMS: 0.3701
- UNDERW: 0.000
- OVERW: 9.000
- ALLCHAN: 848.0
- $\chi^2$/rdf: 13.18 / 11
- P1: 134.8
- P2: 18.06
- P3: 0.1696
- P4: 2.931
- P5: 0.1564E-01
- P6: -0.7335E-02

\[t_0-\text{nonlinear [ns]}\]
c) $2.0 \text{ ns} < \text{diff} < 2.1 \text{ ns}:

\begin{itemize}
  \item ID: 113
  \item Entries: 364
  \item Mean: 18.23
  \item RMS: 0.3759
  \item UDFLW: 0.000
  \item OVFLW: 0.000
  \item ALLCHAN: 388.0
  \item $\chi^2/\text{ndf}$: 10.67 / 8
  \item P1: 54.86
  \item P2: 18.15
  \item P3: 0.1589
  \item P4: 0.8097
  \item P5: 0.0425E-01
  \item P6: 0.2222E-02
\end{itemize}

![Histogram](t0-nonlineart002)

\text{t}_0\text{--nonlinear [ns]}

d) $2.1 \text{ ns} < \text{diff} < 2.2 \text{ ns}:

\begin{itemize}
  \item ID: 114
  \item Entries: 244
  \item Mean: 18.29
  \item RMS: 0.3145
  \item UDFLW: 0.000
  \item OVFLW: 0.000
  \item ALLCHAN: 241.0
  \item $\chi^2/\text{ndf}$: 4.024 / 7
  \item P1: 39.25
  \item P2: 18.21
  \item P3: 0.1598
  \item P4: 8.126
  \item P5: 0.9425E-02
  \item P6: -0.2250E-01
\end{itemize}

![Histogram](t0-nonlineart003)

\text{t}_0\text{--nonlinear [ns]}
e) $2.2 \text{ ns} < \text{diff} < 2.3 \text{ ns}$:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{$t_0$–nonlinear [ns]}
\end{figure}

f) $2.3 \text{ ns} < \text{diff} < 2.4 \text{ ns}$:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{$t_0$–nonlinear [ns]}
\end{figure}
g) Corrected time: $t_0$-nonlinear = $f(\text{diff})$:

\[ y = -1.0238x^2 + 5.0333x + 12.131 \]

h) A final distribution of “$t_0 - t_0$-nonlinear(\text{diff}) +18.0” variable:

\[ \sigma \sim 144 \text{ ps} \]

&

\[ \sigma \sim 238 \text{ ps} \]
Source of “late noise pulses” may be a PMT itself:

a) Trigger on the PiLas pulser; PMT@-1.0kV
   5ns/div, 10mV/div

b) Trigger on the PMT itself; Light pulser off; PMT@-1.0kV.
   5ns/div, 10mV/div

c) A trail of pulses goes for ~5ns.
10. Tune $V_{t1}, V_{t2}$, tau, and $dt_1$ variables with a nonlinear method:

$$v(t) = a \ (t-t_0) \ exp\[-(t_1-t_0)\tau]$$

$$t_0 = t_2*exp[(t_1-t_2)/\tau]-t_1*(V_{t2}/V_{t1})/[exp[(t_1-t_2)/\tau]-(V_{t2}/V_{t1})],$$

1. Tune $V_{t1}$ threshold (nominal 14.8 mV)

![Vt1 threshold graph]

2. Tune $V_{t2}$ threshold (nominal 20.8 mV)

![Vt2 threshold graph]
3. Tune \( V_{t1} \) & \( V_{t2} \) thresholds in tandem

Non-linear extrapolation

- 1.7 < diff < 1.8 ns
- 1.8 < diff < 1.9 ns
- 1.9 < diff < 2.0 ns
- 2.0 < diff < 2.1 ns
- 2.1 < diff < 2.2 ns
- 2.2 < diff < 2.3 ns
- 2.3 < diff < 2.4 ns

Vt1 threshold [mV] (Vt1\&Vt2 move in tandem)

4. Tune Amplifier shaping time (assume nominal 1.5 ns)

Non-linear extrapolation

- 1.7 < diff < 1.8 ns
- 1.8 < diff < 1.9 ns
- 1.9 < diff < 2.0 ns
- 2.0 < diff < 2.1 ns
- 2.1 < diff < 2.2 ns
- 2.2 < diff < 2.3 ns
- 2.3 < diff < 2.4 ns

Amplifier shaping time \( \tau \) [ns]
5. Tune dt1 offset to t1 time (nominal is zero)

![Non-linear extrapolation graph]

**Conclusion:**

I did not find a magic tune.
New conditions:

1) Parametrize the ELANTEK amplifier as a function of gain.

It appears that the response worsens above a gain of 20x:

Gholam’s measurement: 5.8.2002

10x gain: 100mV/div, 2ns/div

![10x gain graph](image1)

20x gain: 100mV/div, 2ns/div

![20x gain graph](image2)

34x gain: 200mV/div, 2ns/div

![34x gain graph](image3)

50x gain: 200mV/div, 2ns/div

![50x gain graph](image4)
2) Decided that the next run will be with a gain of 20x.

My measurement with a light pulser and the PMT connected:
Signal after the splitter before the discriminator:
1ns/div, 10mV/div, 20x. Thresh.: 14.8 & 20.8 mV (1ns/div, 10mV/div, 20x)
Run 21 – Double thresholds, 20x amplifier:

File: new_amp_38.dat, ~100000 triggers, 62.5 µm dia. multi-mode fiber, PiLas laser diode at 5.2%, 10Hz internal trigger, choose the highest gain pad P2-2.

New amplifier board for Elantec EL2075C, 20x charge gain (G_v~13x), which lowers a BW, Split the signal into two LeCroy 4413 discriminators, 14.8mV & 20.8mV thresholds, New high voltage PS made by Matsasuda, Probability of a hit ~ 8142/100000 ~ 8.1%, 22.371 psec/count TDC.

H-8500 new 64-channel PMT with –1.0kV.

1. TDC spectra from each threshold:

a) Low threshold (14.8mV)

b) High threshold (20.8mV)
2. TDC spectrum from a linear extrapolation to base line:
\[ t_0 – \text{corrected} = t_1 - \left( \frac{(t_1 - t_2)}{Vt_1 - Vt_2} \right) \times Vt_1 \]

\( \sigma \sim 131 \text{ ps} \) & \( 255 \text{ ps} \) (no correction)

3. Correlation between \( t_1 \) (TDC1) and \( t_2 \) (TDC2):

\[
\begin{array}{|c|c|c|}
\hline
\text{ID} & \text{ENTRIES} & \text{101} \text{ entries} \\
\hline
\text{Mean} & 0.2502 & 13.87 \\
\text{RMS} & 13.00 & 11.00 \\
\text{UDELW} & 6.168 & 6.192 \\
\text{OVELW} & 6.168 & 6.192 \\
\text{ALLCHAN} & 6.168 & 6.192 \\
\hline
\chi^2/\text{ndf} & 6.679/5 & 6.192 \text{ entries} \\
\text{P1} & 862.2 & 862.2 \\
\text{P2} & 13.87 & 13.87 \\
\text{P3} & 0.1308 & 0.1308 \\
\text{P4} & 300.5 & 300.5 \\
\text{P5} & 13.83 & 13.83 \\
\text{P6} & 0.2551 & 0.2551 \\
\text{P7} & 9.302 & 9.302 \\
\text{P8} & -0.4449 & -0.4449 \\
\text{P9} & -0.1133 & -0.1133 \\
\hline
\end{array}
\]
4. TDC spectrum from a nonlinear extrapolation to base line:

\[ v(t) = a (t-t_0) \exp[-(t_1-t_0)\tau] \]

\[ t_0 = t_2 \times \exp[(t_1-t_2)/\tau]-t_1 \times (Vt_2/Vt_1)/[\exp((t_1-t_2)/\tau)-(Vt_2/Vt_1)], \]

where I have chosen \( \tau = 1.5\text{ns} \).

\[ \sigma \sim 152 \text{ps} \]
\&
\[ 234 \text{ps} \]
(no correction)

5. Correlation between \( t_0 \)-non-linear and \( t_1 \) \& \( t_2 \):
6. Use $t_2$ time to correct $t_1$ time to find the minimum:
$$t_1\text{-corrected} = t_1 - (-0.2012 t_2^2 + 8.8716 t_2 - 78.759 - 18.0)$$

7. Project the distribution to “$t_1$-corrected” axis:

- Incorrect manipulation with the correlated variables?
8. Bin data using a variable $\text{diff} = t_2 - t_1$, in each bin determine the mean non-linear extrapolation to base line, and then combine these to make the overall correction, which is non-linear:

a) Distribution of the diff variable:

![Histogram of diff variable]

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<td>OVERLOW</td>
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<tr>
<td>ALLCHAN</td>
<td>6.92</td>
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</table>

\[\text{diff} = t_2 - t_1 \ [\text{ns}]\]

b) $1.7 \text{ ns} < \text{diff} < 1.8 \text{ ns}$:

![Histogram of diff variable]

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<td>OVERLOW</td>
<td>4.000</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>1912</td>
</tr>
</tbody>
</table>

$\chi^2$/ndf | 60.47 | 14 |
| P1 | 396.1 |
| P2 | 17.81 |
| P3 | 0.1363 |
| P4 | 1.222 |
| P5 | -0.4016 |
| P6 | 0.2394E-01 |
b) 1.8 ns < diff <1.9 ns:

\begin{itemize}
  \item ID = 111
  \item Entries = 2413
  \item Mean = 17.96
  \item RMS = 0.2248
  \item UVFLW = 0.000
  \item OVFLW = 6.000
  \item ALLCHAN = 2407.
\end{itemize}

\[ \chi^2/\text{ndf} = 15.84 / 9 \]

\begin{itemize}
  \item P1 = 481.3
  \item P2 = 17.94
  \item P3 = 0.1373
  \item P4 = -143.9
  \item P5 = -0.1827
  \item P6 = 0.4923
\end{itemize}

\begin{itemize}
  \item t_0–nonlinear [ns]
\end{itemize}

\begin{itemize}
  \item t_0–nonlinear [ns]
\end{itemize}

c) 1.9 ns < diff <2.0 ns:

\begin{itemize}
  \item ID = 112
  \item Entries = 1444
  \item Mean = 18.09
  \item RMS = 0.2296
  \item UVFLW = 0.000
  \item OVFLW = 7.000
  \item ALLCHAN = 1437.
\end{itemize}

\[ \chi^2/\text{ndf} = 14.26 / 13 \]

\begin{itemize}
  \item P1 = 260.2
  \item P2 = 18.06
  \item P3 = 0.1566
  \item P4 = -18.42
  \item P5 = 0.1427E-01
  \item P6 = 0.6275E-01
\end{itemize}

\begin{itemize}
  \item t_0–nonlinear [ns]
\end{itemize}
d) $2.0 \text{ ns} < \text{diff} < 2.1 \text{ ns}$:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{d.png}
\caption{t$_0$–nonlinear [ns]}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
ID & 113 \\
Entries & 248 \\
Mean & 18.20 \\
RMS & 0.2003 \\
UDFLW & 0.000 \\
OVFLW & 0.000 \\
ALLCHAN & 248.0 \\
\hline
$\chi^2$/ndf & 12.58 / 9 \\
F1 & 48.85 \\
F2 & 18.17 \\
F3 & 0.1294 \\
F4 & 4.299 \\
F5 & 0.3057B-01 \\
F6 & 0.1571B-01 \\
\hline
\end{tabular}
\end{table}

e) $2.1 \text{ ns} < \text{diff} < 2.2 \text{ ns}$:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{e.png}
\caption{t$_0$–nonlinear [ns]}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
ID & 114 \\
Entries & 123 \\
Mean & 18.27 \\
RMS & 0.3001 \\
UDFLW & 0.000 \\
OVFLW & 0.000 \\
ALLCHAN & 123.0 \\
\hline
$\chi^2$/ndf & 6.152 / 6 \\
F1 & 18.82 \\
F2 & 18.19 \\
F3 & -0.1699 \\
F4 & -11.60 \\
F5 & -0.1547B-01 \\
F6 & 0.3753B-01 \\
\hline
\end{tabular}
\end{table}
f) $t_0$-corrected (nonlinear) = $f(\text{diff})$:

Time walk correction

\[ y = -1.0238x^2 + 5.0333x + 12.131 \]

diff = abs (t1-t2) [ns]

J.V., 5.13.2002

---

g) Final distribution of $t_0$-linear = $t_0$ – $t_0$-nonlinear +18.0:

$\sigma \sim 128$ ps & 242 ps
New conditions:

- Decided that the final choice will be a gain of 40x.

Gholam’s measurement:
40x gain & LV PS at ±5.6V:
rise time: ~1.54 ns (scope code)
100mV/div, 2ns/div

5.14.2002

40x gain & LV PS at ±6.0V:
rise time: ~1.46 ns (scope code)
100mV/div, 2ns/div

My measurements with a PMT (after the splitter):
10mV/div, 2ns/div & PS at ±6V

5.15.2002

10mV/div, 2ns/div & PS at ±6V, th.: 14.8 & 20.8mV
Run 22 – Double thresholds, 40x amplifier:  

J.V., 5.16.2002  

File: new_amp_39.dat, ~100000 triggers,  
62.5 µm dia. multi-mode fiber, PiLas laser diode at 5.2%, 20Hz internal trigger,  
choose the highest gain pad P2-2.  
New amplifier board for Elantec EL2075C, 40x charge gain (G_v~13x), which lowers a BW,  
Split the signal into two LeCroy 4413 discriminators, 14.8mV & 20.8mV thresholds,  
New high voltage PS made by Matsasuda,  
Probability of a hit ~ 9174/100000 ~ 9.2%,  
22.371 psec/count TDC.  
H-8500 new 64-channel PMT with ~1.0kV.  
Amplifier LV PS at ±6.0Volts to boost the gain a bit.

1. TDC spectra from each threshold:

a) Low threshold (14.8mV)  

b) High threshold (20.8mV)
2. TDC spectrum from a linear extrapolation to base line:
\[ t_{0\text{–corrected}} = t_1 - \frac{(t_1-t_2)}{V_{t_1}-V_{t_2}} \times V_{t_1} \]

\(\sigma \approx 133 \text{ ps} \)

and

\(220 \text{ ps} \)

(no correction)

3. Correlation between \(t_1\) (TDC1) and \(t_2\) (TDC2):
4. TDC spectrum from a nonlinear extrapolation to base line:

\[ v(t) = a \frac{(t-t_0)}{(t_1-t_0)/\tau} \exp[-(t_1-t_0)/\tau] \]

\[ t_0 = t_2 \exp[(t_1-t_2)/\tau] - t_1 \frac{(Vt_2/Vt_1)}{[\exp[(t_1-t_2)/\tau] - (Vt_2/Vt_1)]} \]

where I have chosen \( \tau = 1.5 \text{ns} \).

\[ \sigma \approx 187 \text{ ps} \]

\&

\[ 200 \text{ ps} \]

(no correction)

5. Correlation between \( t_0 \)-non-linear and \( t_1 \) & \( t_2 \):

6. Use \( t_2 \) time to correct \( t_1 \) time to find the minimum:
\[ t_{1-\text{corrected}} = t_1 - (-0.2012 t_2^2 + 8.8716 t_2 - 78.759 - 18.0) \]

7. Project the distribution to “\( t_{1-\text{corrected}} \)” axis:

\[ \sigma \sim 42 \text{ ps} \quad \& \quad 105 \text{ ps} \]

- Incorrect manipulation with the correlated variables?
8. Bin data using a variable \( \text{diff} = t_2 - t_1 \), in each bin determine the mean \textit{non-linear} extrapolation to base line, and then combine these to make the overall correction, which is \textit{non-linear}:

\[
v(t) = a \ (t-t_0) \ \exp[-(t_1-t_0)\tau]
\]

\[
t_0 = t_2 * \exp[(t_1-t_2)/\tau] - t_1 * (V_{t_2}/V_{t_1}) /[\exp[(t_1-t_2)/\tau] - (V_{t_2}/V_{t_1})]
\]

where I have chosen \( \tau = 1.5 \text{ns} \).

a) Distribution of the \text{diff} variable:
b) $1.7 \text{ ns} < \text{diff} < 1.8 \text{ ns}$:

\[
\begin{array}{|c|c|}
\hline
\text{ID} & 110 \\
\hline
\text{Entries} & 880 \\
\hline
\text{Mean} & 17.93 \\
\hline
\text{RMS} & 0.1800 \\
\hline
\text{UDRLW} & 0.000 \\
\hline
\text{OVFLW} & 3.000 \\
\hline
\text{ALLCHAN} & 877.0 \\
\hline
\chi^2/\text{ndf} & 17.99 / 6 \\
\hline
P1 & 107.4 \\
\hline
P2 & 17.90 \\
\hline
P3 & 0.1220 \\
\hline
P4 & -66.89 \\
\hline
P5 & -0.1143E-01 \\
\hline
P6 & 0.2195 \\
\hline
\end{array}
\]

\[t_0-\text{nonlinear [ns]}\]

b) $1.8 \text{ ns} < \text{diff} < 1.9 \text{ ns}$:

\[
\begin{array}{|c|c|}
\hline
\text{ID} & 111 \\
\hline
\text{Entries} & 2346 \\
\hline
\text{Mean} & 18.08 \\
\hline
\text{RMS} & 0.2004 \\
\hline
\text{UDRLW} & 0.000 \\
\hline
\text{OVFLW} & 5.000 \\
\hline
\text{ALLCHAN} & 2341 \\
\hline
\chi^2/\text{ndf} & 19.16 / 7 \\
\hline
P1 & 450.2 \\
\hline
P2 & 18.06 \\
\hline
P3 & 0.1500 \\
\hline
P4 & -1.471 \\
\hline
P5 & -0.6040E-02 \\
\hline
P6 & 0.4552E-02 \\
\hline
\end{array}
\]

\[t_0-\text{nonlinear [ns]}\]
c) 1.9 ns < diff < 2.0 ns:

<table>
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<tr>
<td>UDFLW</td>
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<td>OVLFW</td>
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<tr>
<td>ALLCHAN</td>
<td>1711.</td>
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<tr>
<td>( \chi^2 / \text{ndf} )</td>
<td>16.83 / 7</td>
</tr>
<tr>
<td>P1</td>
<td>333.4</td>
</tr>
<tr>
<td>P2</td>
<td>18.21</td>
</tr>
<tr>
<td>P3</td>
<td>0.1350</td>
</tr>
<tr>
<td>P4</td>
<td>-209.7</td>
</tr>
<tr>
<td>P5</td>
<td>-0.1535</td>
</tr>
<tr>
<td>P6</td>
<td>0.6791</td>
</tr>
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</table>

\[ t_0 \text{–nonlinear [ns]} \]

d) 2.0 ns < diff < 2.1 ns:

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<tbody>
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<tr>
<td>UDFLW</td>
<td>0.000</td>
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<tr>
<td>OVLFW</td>
<td>0.000</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>659.0</td>
</tr>
<tr>
<td>( \chi^2 / \text{ndf} )</td>
<td>12.73 / 6</td>
</tr>
<tr>
<td>P1</td>
<td>118.7</td>
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<td>P2</td>
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<td>P3</td>
<td>0.1385</td>
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<tr>
<td>P4</td>
<td>-136.0</td>
</tr>
<tr>
<td>P5</td>
<td>-0.1183</td>
</tr>
<tr>
<td>P6</td>
<td>0.4335</td>
</tr>
</tbody>
</table>

\[ t_0 \text{–nonlinear [ns]} \]
e) 2.1 ns < diff < 2.2 ns:

f) 2.2 ns < diff < 2.3 ns:
g) $2.3 \text{ ns} < \text{diff} < 2.4 \text{ ns}:

\[ y = -1.3929x^2 + 6.6357x + 10.556 \]

J.Va’vra, 2001-2003 period, the last entry is on February 9, 2003
g) Final distribution of $t_0$-linear = $t_0$ – $t_0$-nonlinear +18.0:

$$\sigma \sim 125 \text{ ps} \quad \& \quad 193 \text{ ps}$$

- This plot was used in the Pylos and IEEE papers!!

<p>| | |</p>
<table>
<thead>
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<tr>
<td>RMS</td>
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<td>UDFLW</td>
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<td>OVFLW</td>
<td>10.00</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>6494</td>
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<tr>
<td>$\chi^2$/ndf</td>
<td>61.81 / 18</td>
</tr>
<tr>
<td>P1</td>
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<td>17.99</td>
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<td>P4</td>
<td>97.14</td>
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<td>P5</td>
<td>18.15</td>
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<td>P6</td>
<td>0.1925</td>
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<tr>
<td>P7</td>
<td>0.1020</td>
</tr>
<tr>
<td>P8</td>
<td>0.3077E-01</td>
</tr>
<tr>
<td>P9</td>
<td>0.3211E-02</td>
</tr>
</tbody>
</table>
9. Is the nonlinear pulse shape \( v(t) = a (t-t_0) \exp[-(t_1-t_0)/\tau] \) actually a good approximation of the H-8500 pulse? Analyze the digital waveform from Gholam’s bench test (no PMT attached):

**Answer: No !!!**

Modeling of H-8500 pulse shape

![Modeling of H-8500 pulse shape](image)

One can do better with a function (in leading edge section anyway):

\[
v(t) = [a (t-t_0) + b (t-t_0)^2] \exp\{-[\alpha + \beta (t_1-t_0) + \gamma (t_1-t_0)^2]/\tau\}
\]

where

\[
a = -0.18, \quad b = 1.58, \quad \alpha = 1.5, \quad \beta = -0.45, \quad \gamma = 0.805 \quad \text{and} \quad \tau = 1.5.
\]

Therefore, it is more complicated to calculate \( t_0 \)!
Simplify with a simple quadratic approximation:

Modeling of the leading edge of the H-8500 pulse

\[ y = 0.4189x^2 - 0.0103x \]
Some new information from Hamamatsu:

1) The Flat Panel PMT H-8500, which we have at SLAC is an early production. Since then the quality has improved.

2) Increasing the gain is possible by increasing the number of dynode stages. However, this is not what you want. One wants to increase the cathode-to-dynode voltage, which is not easy to increase. They can select a good tube having a gain of $5 \times 10^6$.

3) It is very difficult to get less than 100 ps TTS by the present Flat Panel PMT. They need further R&D and money to pursue 100ps TTS. It is not clear how much is needed. According to their new specification of H8500, TTS is 400ps (FWHM), hence 170ps in sigma. To reduce it by half is not an easy task. They will think about the problem.

4) They continue development of new geometry. They already have a 16x16 array, which means 3x3 mm$^2$ pad size. You can make it to 3x12 mm$^2$ by connection 4 straight pads. This kind of modification is possible.
The 1-st PMT – Serial #ZA01542:
(received on 5.25.2001; average gain ~ 0.8 x 10^6; cathode luminous sensitivity ~ 53.9 µA/lm)

The 2-nd PMT – Serial #ZA1932 (slightly more uniform):
(received on 7.22.2002; average gain ~ 1.57 x 10^6; cathode luminous sensitivity ~ 54.5 µA/lm)
“Charge sharing” effect on the boundary of two pads:

a) Sum number of counts on the pad boundary (Mayank’s plot):

![Graph showing the effect of charge sharing on the boundary of two pads with laser diodes positioned.

1) Laser diode positioned on the center between pads 1 and 2

Event #1, Pads 1 and 2, 2ns/div, 20mV/div

Event #2, Pads 1 and 2, 2ns/div, 20mV/div

Event #3, Pads 1 and 2, 2ns/div, 20mV/div

Multiple events, Pads 1 and 2, 2ns/div, 20mV/div
2) Laser diode positioned on the center of pad 1:

Multiple events, Pads 1 and 2, 2ns/div, 20mV/div

Signal gets larger on pad 1, we see nothing on pad 2. We are dealing with a sharing of the amplified charge

b) Make an “OR” of counts on the pad boundary (Mayank’s plot):
c) Relative efficiency with a large ref. PMT (Mayank and Joe):

![Graph showing efficiency relative to big PMT](image1)

d) Relative efficiency with a DIRC ref. PMT (Mayank and Joe):

![Graph showing efficiency relative to small/DIRC PMT](image2)
Pad #1 TDC spectrum during a scan (from Mayank):

Why is it so much wider? Check with a scope:
Old PiLas pulser:

1ns/div, 10mV/div

1ns/div, 10mV/div

2ns/div, 10mV/div

2ns/div, 10mV/div

9.19.2002

Clearly, see much larger jitter than what I had in the beginning of the measurements. The large consistent with the TDC peak width measurements.
New PiLas pulser:

1ns/div, 10mV/div

1ns/div, 10mV/div

2ns/div, 10mV/div

See a similar jitter, i.e., the pulser is not a cause of the jitter pulser.
Old PiLas pulser: 10.3.2002

Find that the “trigger out” pulse was a NIM pulse rather than a TTL pulse (one can choose). Probably a mistake when recreating the setup in the bldg. 403.
The 3-rd PMT – Serial #ZA1964 (2:1:1:...:1 resistor chain):
(received on 9.25.2002; average gain \( \sim 1.22 \times 10^6 \); cathode luminous sensitivity \( \sim 60.9 \mu A/\text{lm} \))

Elantek amplifier 40x,
PMT at \(-1.0kV\),
Chain: \(2:1:1:...:1\),
New Pilas laser diode,
50\(\mu\)m dia. fiber
Run 23 – Double thresholds, a new 2:1:1:...:1 chain: J.V., 11.2.2002

- File: pmt-3_1.dat, ~100000 triggers,
- 62.5 µm dia. multi-mode fiber, PiLas laser diode at 8.4%, 1kHz internal trigger, Pad 13,
- Elantec EL2075C, amplifier with a 40x charge gain (Gv~13x), which lowers a BW
- Split the signal passively into two LeCroy 4413 discriminators, 14.8mV & 20.8mV thresholds,
- Probability of a hit ~ 6450/100000 ~ 6.5% only,
- 24.0 psec/count TDC (a new calibration),
- H-8500 with a modified resistor chain 2:1:1:...:1, HV at –1.0kV.

1. TDC spectra from each threshold:
   a) Low threshold (Vt1=14.8mV)

```
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<td>RMS</td>
<td>37.34</td>
</tr>
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<td>UDFLW</td>
<td>2.000</td>
</tr>
<tr>
<td>OVLFW</td>
<td>8.000</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>6440</td>
</tr>
</tbody>
</table>
```
2. TDC spectrum from a linear extrapolation to base line:

\[
t_{0\text{-corrected}} = t_{1} - \left(\frac{(t_{1}-t_{2})}{V_{t1}-V_{t2}}\right) \times th_{1}
\]

\[\sigma \sim 221 \text{ ps} \quad \& \quad 380 \text{ ps}\]
3. Bin data using a variable \( \text{diff} = t_2 - t_1 \), in each bin determine the mean non-linear extrapolation to base line, and then combine these to make the overall correction, which is non-linear:

\[
v(t) = a (t-t_0) \exp[-(t_1-t_0)\tau] \\
t_0 = t_2 \exp[(t_1-t_2)/\tau] - t_1 \cdot (V_{t_2}/V_{t_1})/[\exp[(t_1-t_2)/\tau]-(V_{t_2}/V_{t_1})],
\]

where I have chosen \( \tau = 1.5\text{ns} \).

a) Distribution of the diff variable:

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<th>108</th>
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<tbody>
<tr>
<td>Entries</td>
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<tr>
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<td>2.394</td>
</tr>
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<td>RMS</td>
<td>0.1329</td>
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<td>UDFLOW</td>
<td>0.000</td>
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<td>OVFLOW</td>
<td>3.000</td>
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<tr>
<td>ALLCHAN</td>
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</tbody>
</table>

\[
\text{diff} = t_2 - t_1 \ [\text{ns}] 
\]
b) $2.25 \text{ ns} < \text{diff} < 2.3 \text{ ns}:$

\begin{align*}
\text{ID} & \quad 110 \\
\text{Entries} & \quad 365 \\
\text{Mean} & \quad 8.797 \\
\text{RMS} & \quad 0.3119 \\
\text{UDFLW} & \quad 0.000 \\
\text{OVLFW} & \quad 0.000 \\
\text{ALLCHAN} & \quad 365.0 \\
\chi^2/\text{ndf} & \quad 5.960 / 2 \\
P1 & \quad 64.41 \\
P2 & \quad 8.603 \\
P3 & \quad 0.140 \\
P4 & \quad -132.9 \\
P5 & \quad 0.3043 \\
P6 & \quad 2.075
\end{align*}

\begin{align*}
\text{t}_0-\text{nonlinear [ns]}
\end{align*}

b) $2.3 \text{ ns} < \text{diff} < 2.35 \text{ ns}:

\begin{align*}
\text{ID} & \quad 111 \\
\text{Entries} & \quad 1707 \\
\text{Mean} & \quad 8.534 \\
\text{RMS} & \quad 0.3175 \\
\text{UDFLW} & \quad 0.000 \\
\text{OVLFW} & \quad 0.000 \\
\text{ALLCHAN} & \quad 1707.0 \\
\chi^2/\text{ndf} & \quad 30.00 / 6 \\
P1 & \quad 262.4 \\
P2 & \quad 8.398 \\
P3 & \quad 0.2518 \\
P4 & \quad -349.1 \\
P5 & \quad -1.767 \\
P6 & \quad 4.981
\end{align*}

\begin{align*}
\text{t}_0-\text{nonlinear [ns]}
\end{align*}
c) $2.35 \text{ ns} < \text{diff} < 2.4 \text{ ns:}$

![Diagram](image1)

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<td>ALLCHAN</td>
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<tr>
<td>P4</td>
<td>4.872</td>
</tr>
<tr>
<td>P5</td>
<td>0.2870</td>
</tr>
<tr>
<td>P6</td>
<td>0.1485E-02</td>
</tr>
</tbody>
</table>

$t_0$–nonlinear [ns]

---

d) $2.4 \text{ ns} < \text{diff} < 2.45 \text{ ns:}$

![Diagram](image2)

<table>
<thead>
<tr>
<th>ID</th>
<th>113</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>633</td>
</tr>
<tr>
<td>Mean</td>
<td>8.707</td>
</tr>
<tr>
<td>RMS</td>
<td>0.2886</td>
</tr>
<tr>
<td>UDFLW</td>
<td>0.000</td>
</tr>
<tr>
<td>OVFLW</td>
<td>0.000</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>633.0</td>
</tr>
<tr>
<td>$\chi^2/\text{ndf}$</td>
<td>8.452 / 12</td>
</tr>
<tr>
<td>P1</td>
<td>91.47</td>
</tr>
<tr>
<td>P2</td>
<td>8.685</td>
</tr>
<tr>
<td>P3</td>
<td>0.2694</td>
</tr>
<tr>
<td>P4</td>
<td>-7.030</td>
</tr>
<tr>
<td>P5</td>
<td>0.4391E-01</td>
</tr>
<tr>
<td>P6</td>
<td>0.8980E-01</td>
</tr>
</tbody>
</table>

$t_0$–nonlinear [ns]
e) $2.45 \text{ ns} < \text{diff} < 2.5 \text{ ns}$:

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{ID} & 114 \\
\textbf{Entries} & 340 \\
\textbf{Mean} & 8.811 \\
\textbf{RMS} & 0.2934 \\
\textbf{UDFLW} & 0.000 \\
\textbf{OVFLW} & 0.000 \\
\textbf{ALLCHAN} & 340.0 \\
\hline
\textbf{$\chi^2$/ndf} & 7.594 / 10 \\
\hline
\end{tabular}
\end{center}

\begin{center}
$t_0$–nonlinear [ns]
\end{center}

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{P1} & 46.46 \\
\textbf{P2} & 8.775 \\
\textbf{P3} & 0.2734 \\
\textbf{P4} & -6.883 \\
\textbf{P5} & 0.1779E-02 \\
\textbf{P6} & 0.1246 \\
\hline
\end{tabular}
\end{center}

f) $2.5 \text{ ns} < \text{diff} < 2.55 \text{ ns}$:

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{ID} & 115 \\
\textbf{Entries} & 219 \\
\textbf{Mean} & 8.923 \\
\textbf{RMS} & 0.2813 \\
\textbf{UDFLW} & 0.000 \\
\textbf{OVFLW} & 0.000 \\
\textbf{ALLCHAN} & 219.0 \\
\hline
\textbf{$\chi^2$/ndf} & 11.04 / 9 \\
\hline
\end{tabular}
\end{center}

\begin{center}
$t_0$–nonlinear [ns]
\end{center}

\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{P1} & 29.95 \\
\textbf{P2} & 8.915 \\
\textbf{P3} & 0.2519 \\
\textbf{P4} & -3.600 \\
\textbf{P5} & 0.2037E-01 \\
\textbf{P6} & 0.5752E-01 \\
\hline
\end{tabular}
\end{center}
g) $2.55 \text{ ns} < \text{diff} < 2.6 \text{ ns}:

f) $t_0$-corrected (nonlinear) = $f(\text{diff})$:

Time walk correction for pmt-3_1.dat

$y = -20.303x^3 + 150.09x^2 - 367.66x + 307.18$
g) Final distribution of $t_0$-linear = $t_0 - t_0$-nonlinear + 8.0:

\[ \sigma \sim 231 \text{ ps} \]
\[ \sigma \sim 351 \text{ ps} \]

- It is worse that results with the PMT-1!!
Run 24 – Double thresholds, 400x amplification: J.V., 11.3.2002

File: pmt-3_2.dat, ~100000 triggers, 62.5 µm dia. multi-mode fiber, PiLas laser diode at 9.8%, 1kHz internal trigger, Pad 13, Elantec EL2075C, amplifier with a 40x charge gain (G_v~13x), add Philips 715 10x amplifier, Split the signal passively into two LeCroy 4413 discriminators, 100mV & 150mV thresholds, Probability of a hit ~ 13892/100000 ~ 13.9% only, 24.0 psec/count TDC, H-8500 with a modified resistor chain 2:1:1:...:1, HV at −1.0kV.

1. TDC spectra from each threshold:
   b) Low threshold (V_t=100mV)

<table>
<thead>
<tr>
<th>ID</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>13892</td>
</tr>
<tr>
<td>Mean</td>
<td>850.8</td>
</tr>
<tr>
<td>RMS</td>
<td>31.01</td>
</tr>
<tr>
<td>UDFLW</td>
<td>2.000</td>
</tr>
<tr>
<td>OVFLW</td>
<td>8.000</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>0.1388E+05</td>
</tr>
</tbody>
</table>
J. Va’vra, 2001-2003 period, the last entry is on February 9, 2003

b) Low threshold (Vt1=100mV)

c) High threshold (Vt2=150mV)

2. TDC spectrum from a linear extrapolation to base line:

\[ t_0 – \text{corrected} = t_1 - \left(\frac{(t_1-t_2)/Vt_1-Vt_2)}{Vt_1-Vt_2}\right) \times th_1 \]

\[ \sigma \sim 180 \text{ ps} \]

&

\[ \sigma \sim 256 \text{ ps} \]

Fit:

\[ G1+G2+a+bx+cx^2 \]
3. Bin data using a variable $\text{diff} = t_2 - t_1$, in each bin determine the mean **non-linear** extrapolation to base line, and then combine these to make the overall correction, which is **non-linear**:

$$v(t) = a (t-t_0) \exp[-(t_1-t_0)\tau]$$

$$t_0 = t_2 \exp[(t_1-t_2)/\tau] - t_1 \frac{(V_{t_2}/V_{t_1})}{[\exp[(t_1-t_2)/\tau]-(V_{t_2}/V_{t_1})]}$$

where I have chosen $\tau = 1.5\text{ns}$.

a) Distribution of the diff variable:

<table>
<thead>
<tr>
<th>ID</th>
<th>108</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>13892</td>
</tr>
<tr>
<td>Mean</td>
<td>2.573</td>
</tr>
<tr>
<td>RMS</td>
<td>0.2547</td>
</tr>
<tr>
<td>UDEFW</td>
<td>1.000</td>
</tr>
<tr>
<td>OVFLW</td>
<td>1145</td>
</tr>
<tr>
<td>ALLCHAN</td>
<td>0.1275E+05</td>
</tr>
</tbody>
</table>

![Graph showing the distribution of diff variable]
b) $1.85 \text{ ns} < \text{diff} < 1.90 \text{ ns}$:

![Graph showing t₀–nonlinear [ns] distribution for 1.85 ns < diff < 1.90 ns]

- ID: 110
- Entries: 2623
- Mean: 18.49
- RMS: 0.3914
- UDFL W: 48.00
- OVFL W: 5.000
- ALLCHAN: 2570

$\chi^2/\text{ndf} = 63.31/8$

- P1: 527.7
- P2: 18.43
- P3: 0.1717
- P4: -633.1
- P5: 54.69
- P6: -1.070

b) $1.90 \text{ ns} < \text{diff} < 1.95 \text{ ns}$:

![Graph showing t₀–nonlinear [ns] distribution for 1.90 ns < diff < 1.95 ns]

- ID: 111
- Entries: 3996
- Mean: 18.70
- RMS: 0.3923
- UDFL W: 232.0
- OVFL W: 17.00
- ALLCHAN: 3647

$\chi^2/\text{ndf} = 27.88/7$

- P1: 671.8
- P2: 18.53
- P3: 0.1989
- P4: -251.2
- P5: 0.5638E-01
- P6: 0.7512
c) $1.95 \text{ ns} < \text{diff} < 2.00 \text{ ns}$:

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDELW</th>
<th>OVERLW</th>
<th>ALLCHAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>766</td>
<td>18.93</td>
<td>0.4291</td>
<td>77.00</td>
<td>1.000</td>
<td>688.0</td>
</tr>
</tbody>
</table>

\[ \chi^2/\text{ndf} = 9.18 / 6 \]

- \( P_1 = 137.2 \)
- \( P_2 = 18.84 \)
- \( P_3 = 0.1900 \)
- \( P_4 = -1.54 \)
- \( P_5 = 0.1516 \)
- \( P_6 = 0.3130 \)

**t\textsubscript{0}–nonlinear [ns]**

\[ 18 \quad 18.5 \quad 19 \quad 19.5 \quad 20 \quad 20.5 \quad 21 \quad 21.5 \quad 22 \quad 22.5 \quad 23 \]

\[ t_0–nonlinear [ns] \]

\[ 18 \quad 18.5 \quad 19 \quad 19.5 \quad 20 \quad 20.5 \quad 21 \quad 21.5 \quad 22 \quad 22.5 \quad 23 \]

\[ t_0–nonlinear [ns] \]

\[ 18 \quad 18.5 \quad 19 \quad 19.5 \quad 20 \quad 20.5 \quad 21 \quad 21.5 \quad 22 \quad 22.5 \quad 23 \]

\[ t_0–nonlinear [ns] \]

d) $2.00 \text{ ns} < \text{diff} < 2.05 \text{ ns}$:

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDELW</th>
<th>OVERLW</th>
<th>ALLCHAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>113</td>
<td>850</td>
<td>19.34</td>
<td>0.3779</td>
<td>59.00</td>
<td>3.000</td>
<td>798.0</td>
</tr>
</tbody>
</table>

\[ \chi^2/\text{ndf} = 29.17 / 6 \]

- \( P_1 = 137.1 \)
- \( P_2 = 18.97 \)
- \( P_3 = 0.2196 \)
- \( P_4 = -120.3 \)
- \( P_5 = 0.1618 \)
- \( P_6 = 0.3205 \)
e) $2.05 \text{ ns } < \text{diff} < 2.10 \text{ ns}$:

![Histogram](image1.png)

f) $2.10 \text{ ns } < \text{diff} < 2.15 \text{ ns}$:

![Histogram](image2.png)
f) \( t_0 \)-corrected (nonlinear) = \( f(\text{diff}) \):

Time walk correction for pmt-3_2.dat

\[
y = -6.2143x^2 + 27.794x - 11.836
\]

g) Final distribution of \( t_0 \)-linear = \( t_0 - t_0 \)-nonlinear +18.0:

\[ \sigma \sim 171 \text{ ps} \]

- Again, the resolution is worse than the results with the PMT-1!

New aperture:

Side view:
- Measure also a focal length of the fiber optics system by shining a laser into it.
Scan #1 of H-8500 PMT #1: T.Hadig, Mayank, Joe and J.V..11.18.2002.
62.5 µm dia. multi-mode fiber, 20kHz internal trigger,
Elantec EL2075C amplifier (charge gain 40x, voltage gain ~13x),
LeCroy 4413 discriminators with 15mV threshold, LeCroy TDCs with 0.5ns/count,
X-step: 0.1mm, Y-step: 1mm, Events/point: 40000, Probability of a hit: ~10%,
Scan #2 of H-8500 PMT #2:
Ratio of response of Scan #2/Scan #1:

\[
\frac{\text{Scan #2}}{\text{Scan #1}}
\]
Imaging objects with H-8500 PMT #2:
Projection of one line scan of PMT#2:
- Step size: 25 microns

- See clearly the electrode structure.

Detailed scan of one pad in H-8500 PMT #2:

Red laser diode PiLas at 635nm, 62.5 μm dia. multi-mode fiber, 20kHz internal trigger, Elantec EL2075C amplifier (charge gain 40x, voltage gain ~13x), LeCroy 4413 discriminators with 15mV threshold, LeCroy TDCs with 0.5ns/count, X-step: 0.1mm, Y-step: 1mm, Events/point: 40000, Probability of a hit: a few %. H-8500 #2 in sequence.

- At 635nm, one cannot trust the QE.
Run 25 – **Philips 715 CFD, and 400x amplification:**

J.V., 1.23.2003

File: pmt-1_1a.dat, 100000 triggers,

Logic of this test: Try to accomplish a equally good result as obtained with the urle MCP-PMT with exactly the same electronics,

4 µm dia. single-mode fiber, the 2-nd new PiLas laser diode at 22.4% (!?!), 1kHz internal trigger,

Elantec EL2075C amplifier (40x), add a 275MHz BW Philips 779 amplifier (10x); total ch. gain 400x,

AC coupling after the 779 amplifier to remove a slight DC offset,

Philips constant fraction 715 discriminator (CF) with 30mV threshold and 2ns delay cable,

The threshold is equivalent to a 3 threshold with Elantek amp. only,

Probability of a hit ~ 3311/100000 ~ 3.3%,

24 psec/count TDC,

Hamamatsu H-8500 PMT at –1.0kV.

![Diagram of PMT setup](image)

**Histogram:**

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDFL W</th>
<th>OVERW</th>
<th>ALLCHAN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3311</td>
<td>859.0</td>
<td>24.59</td>
<td>24.00</td>
<td>35.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td>3252</td>
</tr>
</tbody>
</table>

**Time [counts]**
σ ~ 138 ps & 244 ps

- Hamamatsu H-8500 PMT yields worse timing resolution compared to Burle MCP-PMT.
Summary of all results with H-8500:  
J.V., 2.8.2003

<table>
<thead>
<tr>
<th>Run</th>
<th>PMT #</th>
<th>Ampl. gain</th>
<th>Method of extrapolation</th>
<th>Other comments</th>
<th>Th₁ [mV]</th>
<th>Th₂ [mV]</th>
<th>σ₁ [ps] (A₁)</th>
<th>σ₂ [ps] (A₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1</td>
<td>50</td>
<td>Linear</td>
<td>Use a simple straight line</td>
<td>14.8</td>
<td>20.8</td>
<td>131 (304.6)</td>
<td>309 (210.4)</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>50</td>
<td>Nonlinear</td>
<td>Use a pulse shape</td>
<td>14.8</td>
<td>20.8</td>
<td>157 (272.0)</td>
<td>234 (259.2)</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>50</td>
<td>Linear</td>
<td>Use a “diff” variable</td>
<td>14.8</td>
<td>20.8</td>
<td>150 (281.2)</td>
<td>249 (39.3)</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>50</td>
<td>Nonlinear</td>
<td>Use a “diff” variable</td>
<td>14.8</td>
<td>20.8</td>
<td>144 (268.5)</td>
<td>238 (58.81)</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>20</td>
<td>Linear</td>
<td>Use a simple straight line</td>
<td>14.8</td>
<td>20.8</td>
<td>131 (862.2)</td>
<td>255 (300.5)</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>20</td>
<td>Nonlinear</td>
<td>Use a “diff” variable</td>
<td>14.8</td>
<td>20.8</td>
<td>128 (576.3)</td>
<td>242 (67.55)</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>40</td>
<td>Linear</td>
<td>Use a simple straight line</td>
<td>14.8</td>
<td>20.8</td>
<td>133 (836.5)</td>
<td>220 (211.6)</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>40</td>
<td>Nonlinear</td>
<td>Use a “diff” variable</td>
<td>14.8</td>
<td>20.8</td>
<td>125 (604.2)</td>
<td>193 (97.14)</td>
</tr>
<tr>
<td>23</td>
<td>3</td>
<td>40</td>
<td>Linear</td>
<td>Use a simple straight line</td>
<td>14.8</td>
<td>20.8</td>
<td>221 (375.6)</td>
<td>380 (255.4)</td>
</tr>
<tr>
<td>23</td>
<td>3</td>
<td>40</td>
<td>Nonlinear</td>
<td>Use a “diff” variable</td>
<td>14.8</td>
<td>20.8</td>
<td>231 (351.2)</td>
<td>352 (110.7)</td>
</tr>
<tr>
<td>24</td>
<td>3</td>
<td>400</td>
<td>Linear</td>
<td>Use a simple straight line</td>
<td>100</td>
<td>150</td>
<td>180 (1983)</td>
<td>256 (394.5)</td>
</tr>
<tr>
<td>24</td>
<td>3</td>
<td>400</td>
<td>Nonlinear</td>
<td>Use a “diff” variable</td>
<td>100</td>
<td>150</td>
<td>171 (1509)</td>
<td>473 (109.5)</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>400</td>
<td>-</td>
<td>Use a Philips CDF</td>
<td>30</td>
<td>-</td>
<td>138 (507)</td>
<td>244 (110)</td>
</tr>
</tbody>
</table>

- In Pylos and at IEEE, we have quoted the “125 & 193ps” result.
- In practice, we probably are not much better than ~130-140ps.
- The 3-rd tube with a 2:1:1:…:1 chain is not really better so far.
- The Philips CDF with the 400x amplification did not help.