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Tests of 3" Photomultiplier Tubes for the CLAS TOF

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1 Overview

The large-angle Time-of-Flight (TOF) system for the CEBAF Large Acceptance Spectrometer (CLAS) covers an area of 178 m^2. Each sector is comprised of 2" thick plastic scintillator and a total area of 30 m^2 and instrumented with 52 channels of electronics, that is 26 scintillator units, with an average size of $5\times30\times400$ cm^3. The goal is to achieve a time resolution of $\sigma \sim 200$ ps over the entire area. The standard approach of using two 2" photomultiplier tubes (PMTs), one on each end of the scintillator with fish-tail light guides, is limited by the small area of light collected by the PMTs.

The contributions to the measured time resolution of the TOF system may be parametrized as [1]:

$$\sigma_{TOT} = \sqrt{\sigma_0{}^2 + \frac{\sigma_{SCI}{}^2 + \sigma_{PMT}{}^2 + (\sigma_P \cdot d)^2}{N_{pe}}} \qquad (1)$$

where,

$$\begin{aligned} \sigma_0 &\sim 30 - 75\ ps \\ \sigma_{SCI} &\sim 890\ ps \\ \sigma_{PMT} &\sim 740\ ps \\ \sigma_P &\sim 840\ ps/m \end{aligned}$$

are single-photoelectron responses for the scintillator, PMT and path length variations in the light collection. σ_0 represents the intrinsic resolution of the electronic measuring system. Path length variations in the scintillator scale with the distance, d, from the source to the PMT. The statistical behavior of the first three terms is indicated by scaling the single-photoelectron responses by $\sqrt{N_{pe}}$, where N_{pe} is the average number of photoelectrons seen by the PMT. For scintillators which are several meters in length, the dominant contribution comes from transit time variations of photon paths in the scintillator (σ_P). [1]

In the forward-angle TOF system, we have 264 2" PMTs which results in 113 cm^2 of photocathode area per m^2 of active detector. The large angle system will be instrumented with 312 channels, resulting in 26 cm^2 of photocathode area per m^2 of detector if we use single 2" tubes on each channel. This results in a factor of 4.3 less photomultiplier tube coverage. The purpose of this study is to study alternatives to increase the photocathode coverage per active area of TOF detector which have minimal impact on overall cost. The cost of photocathode area decreases for large tubes. However, the mechanical design and light guides become more complicated. Therefore, we have chosen to study the impact of using 3" PMTs on time resolution which might provide a viable solution for the large-angle counters.

2 PMT Transit Time

We have measured several characteristics of four 3" tubes, Thorn EMI 9821B, Philips XP2312B and XP4312B/D1, and Hamamatsu H5540. [2] We also measured the same parameters for the 2" Thorn EMI 9954A PMT which was selected for the forward-angle TOF scintillators. In Table 1 we list relevant parameters of each of the tubes.

The relative transit times of the PMTs were measured by illuminating a small area of the photocathode with a fiber light source [2]. Figures 1-5 show the pulse height and time response of our four tubes for two orthogonal

[1]The value for σ_P given in Equation (1) is estimated assuming light rays produced in the scintillator within the critical angle are collected uniformly into the PMT. The measured value of σ_P=1460±280 ps/m [1] is substantially larger. If a light collection system is used which selects rays within the 30° cone, σ_P could be reduced to 240 ps/m. In this last instance, σ_P is not the dominant term in the resolution.

[2]The H5540 is the voltage divider and magnetic shield assembly containing the R5004 PMT.

Table 1: Selected parameters for the photomultiplier tubes we have tested. These were taken from the manufacturers specifications. All tubes are have a linear focused dynode structure.

Parameter	*Thorn EMI 9954A*	*Thorn EMI 9821B*	*Philips XP2312B*	*Philips XP4312B*	*Hamamatsu H5540*
Stages	12	12	12	10	8
Nominal Diam (mm)	46	60	68	68	65
Measured Diam (mm)	45	66	72	62	66
Area Ratio	1	1.7	2.2	2.2	2.0
Rise time (ns)	2	2.1	2.5	2.1	2.0
Transit time (ns)	41	38	35	–	–
Gain ($\times 10^6$)	6	6	6	1	1

scans across the cathode. The pulse height response indicate that the effective photocathode diameters quoted by the manufacturers (see Table 1) are sometimes larger and sometimes smaller than what we measure. Variations between tubes of the same type were not studied systematically.

The measured transit times may be used to calculate the root-mean-square (RMS) time spread of PMT pulses for uniform illumination assuming azimuthal symmetry with the following prescription (r is the radial coordinate):

$$\begin{aligned} \langle t \rangle &= \frac{\sum t(r)|r|}{\sum |r|} \\ \langle t^2 \rangle &= \frac{\sum t(r)^2|r|}{\sum |r|} \\ \sigma_{PMT} &= \sqrt{\langle t^2 \rangle - \langle t \rangle^2} \end{aligned} \qquad (2)$$

While this assumption is not valid *a priori*, scans across different diameters yield similar values for the computed RMS. The computed values are given in Table 2 and may be used together with Equation (1) to estimate this contribution to the time resolution of the counter. All tubes measured, except the Hamamatsu H5540, have RMS values which could be considered for our

Table 2: RMS variations computed for uniform illumination from the measured transit time across the face of the PMT. The two columns correspond to the variations across the center 2" and to the full cathode, as given by the measured diameter in Table 1.

Photomultiplier	*Computed σ (ns) 2" center*	*Computed σ Full Cathode*
Thorn EMI 9954A	0.55	
Thorn EMI 9821B	0.52	0.88
Philips XP2312B (horizontal)	0.16	0.65
Philips XP2312B (vertical)	0.22	0.80
Philips XP4312B (horizontal)	0.07	0.32
Philips XP4312B (vertical)	0.24	0.34
Hamamatsu H5540 (horizontal)	0.31	4.9
Hamamatsu H5540 (vertical)	0.29	3.7

TOF system. We note that in the case of this PMT, good time characteristics are obtained inside a 2.5 cm radius.

3 Cosmic-Ray Tests

We measured the time characteristics of the Thorn EMI 9821B PMT with the same apparatus used previously to compare 2" PMTs [3]. Using a laser source, the time resolution of a single 9821B tube was measured for light uniformly illuminating the central 40 cm of the photocathode. The time response (shown in Figure 6) shows that the central part of the photocathode performs as well as the same area of our 2" tubes. [3]

We next measured the time response of a scintillation counter (BC-408 of size $5 \times 20 \times 300\ cm^3$) instrumented with a standard fish tail light guide and 2" XP2262 tube on one end and the EMI 9921B PMT directly coupled to the other end [4]. No light guide was used on this side, the photocathode coverage of the scintillator was 27.2 cm^2. The test measured the time response to cosmic ray particles traversing the center of the counter, selected

[3] The voltage divider used was kindly provided by the manufacturer.

by two trigger counters ($5 \times 10 \times 20\ cm^3$) which determined the traversal time with a resolution better than $\sigma = 70$ ps. (All quoted results have the appropriate reference counter resolution subtracted.) For a direct comparison, the resolution was also measured after replacing the 3" tube with a 2" 9954A PMT. The resolution is plotted in Figure 7 as a function of HV on the 9821B PMT. The plot indicates that we obtain a resolution of σ=206 ps with the 9921B, compared to σ=251 ps with the 9954A. This implies an improvement of ~50% if the effect is entirely due to the single 9921B PMT, which contributes in quadrature with the XP2262 PMT on the other side of the counter. If one naively scales by the square root of the increased photocathode area, we might expect resolution to improve by 28%. This surprisingly large improvement may be explained if the measurements with the 9954A PMT were not optimized. Previous measurements with 2" tubes gave resolutions on the same counter of σ=200 ps. Because of this fact, we believe that the use of 3" tubes may improve the time resolution, but the effect may not be as large as indicated above.

4 Linearity

As a side measurement, but of general interest, the linearity of the two Amperex tubes and the EMI 9954A PMT were measured. The method used was as follows: The PMT was placed opposite a light-emitting diode inside a light-tight box. The LED was pulsed to emit pulses alternately of high and low intensity. (The intensity ratio was adjusted to fall between three and four.) The LED was mounted on a threaded rod which allowed moving the LED toward or away from the PMT so that the light detected by the PMT changed montotonically. Each LED signal registered by the PMT was digitized and the ratio of alternating pulses was monitored as the LED was moved close to the PMT. The amount of light detected by the PMT was calibrated with the single photoelectron signal. The ratio of pulses is expected to remain constant until the high level signal begins to saturate the PMT, which indicates the beginning of the non-linear range. In Figure 8 we plot the ratio as a function of number of photoelectrons. The 2" EMI 9954A PMT remains linear up to about 3000 photoelectrons, slightly below typical ratings for the tube. The Amperex tubes remain linear beyond 10000 photoelectrons.

Table 3: Two PMTs were coupled to each end of the scintillator. Data were taken when both tubes were passively added into a single electronics channel and when only one tube on each side was active. For reference, measurements on the same scintillator with fish tail light guides and 2" XP2262 PMTs, the measured resolution was σ=354 ps and the estimated N_{pe} was 115. In all cases the number of photoelectrons was estimated by using the ratio of pulse heights of tubes on each end of the scintillator.

EMI 9821B HV1 (V)	*EMI 9821B HV2 (V)*	*XP4312B HV1 (V)*	XP4312 B HV2 (V)	σ *(ps)*	N_{pe} *(estimate)*
1800	2000	2310	2400	247	227
1800	0	0	2400	343	152
0	2000	2310	0	293	148

5 Double PMT Measurements

To increase the photocathode area on each counter, we measured the resolution of a large scintillator with two PMTs on each end, as shown in Figure 9. The PMTs were attached directly on the ends of a 450 $\times$ 30 $\times$ 5 cm^3 BC-408 scintillator, without a light guide. The time resolution was measured for cosmic-ray tracks traversing the center of the scintillator.

To minimize the cost impact of additional tubes, we investigated the cost-saving measure of instrumenting the two PMTs on each side with a single electronic channel. The signals of the two PMTs on each end were passively summed, discriminated and digitized by a LeCroy 2228A TDC. The termination of the signals was accomplished with resistors as shown in Figure 9. (The resolution was measured for various termination schemes, but differences were not significant.) The cable lengths from each PMT were adjusted to be time coincident to within about 200 ps with the Tektronics TDS640 digital oscilloscope. Scope pulses are shown in Figure 10. We estimate that the transit time varies by 100 ps for every 10 V variation of the supply voltage. To study systematic shifts of the resolution with high voltage, the resolution was measured for various voltages on the 3" tubes, shown in Figure 11. We found the resolution to be relatively insensitive to changes in high voltage.

In order to directly compare the results using a single PMT and two

PMTs, we took data using two tubes on each side, and with single tubes on each side by turning off the HV to the other tube. The results are shown in Table 3. The average time resolution using a single PMT on each side is 318 ps. If one adds the results of single tube measurements in quadrature, which assumes each pair of PMTs is perfectly timed, one expects a double tube resolution of 226 ps. We measure 247 ps. Thus, we obtain an improvement in the resolution of 23%, compared to a maximum possible due to statistics of 29%.

6 Conclusions

The intrinsic time performance of the PMT, σ_{PMT}, should not significantly degrade the time resolution of the TOF system, σ_{TOT}. See Equation (1). The time jitter of 3" PMTs is generally worse than it is for 2" tubes, as given in Table 2. However, our measurements indicate that some 3" tubes in fact have better time characteristics, and even when they are slightly worse, the overall time resolution improves due to the increased photocathode coverage. This effect is illustrated in Figure 12, which plots the overall time resolution as a function of PMT radius. (We assume that the number of photoelectrons N_{pe} is proportional to the photocathode area.) For the curves in Figure 12, the contributions to the resolution are given in Equation (1) for two different values of σ_{PMT}. In that case, the overall resolution for a 2" PMT is $\sigma_{TOT} =$ 216 ps, but $\sigma_{TOT} = 159$ ps for a 3" PMT with a $\sigma_{PMT} = 880$ ps. While this conclusion may be modified if other contributions to the total resolution are smaller than expected, we conclude that 3" tubes are a cost-effective solution for our system.

We have also tested the effectiveness of passively combining two PMTs into a single electronics channel. We conclude that the effort in adjusting the relative times of the two PMTs relative to one another is reasonable and can be accomplished using an oscilloscope. The increased resolution for this solution is 80% of the gain expected by instrumenting both PMTs.

ACKNOWLEDGEMENTS

This report is a summary of a several of tests which are applicable to our detector and thus many persons have contributed in various ways to the end product. We would like to thank Hamlet Mkrtchyan for performing some of the transit time measurements; and Ashot Gasparian and Ioana Niculescu for assistance with the PMT linearity tests. We would also like to acknowledge useful conversations with the representatives of the photomultiplier manufacturers.

References

[1] M. Kuhlen *et.al.*, NIM **A301**, 223 (1991).

[2] See for example, Detector Meisters, "Preliminary Amplitude and Time Response Scans of an XP4312B PMT," November 4, 1992.

[3] E.S. Smith and R. Jacobs, "Photomultiplier Tests for the CLAS TOF," CLAS-NOTE-91-003, February, 1991.

[4] H. Llewellyn, "Photomultiplier Tests for the CLAS TOF System," Masters Thesis, Virginia State University, May 1993.

List of Figures

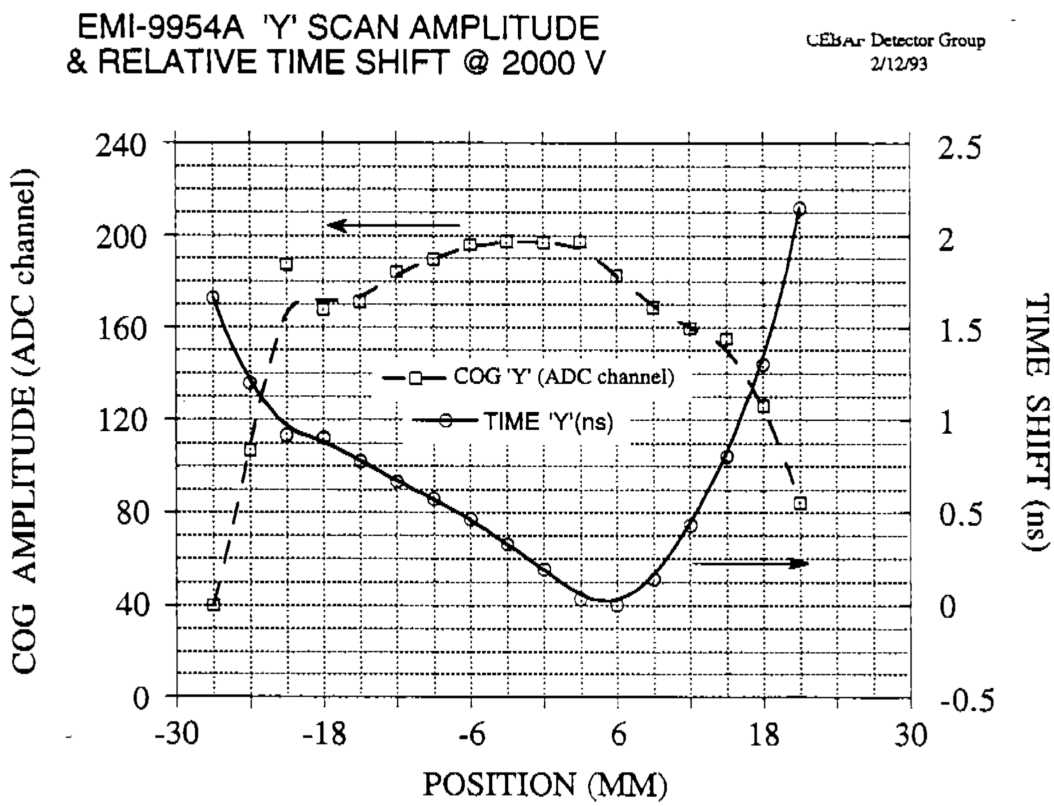


Figure 1: Transit time and pulse height variations for the Thorn EMI 9954A along a diameter of the 2" tube.

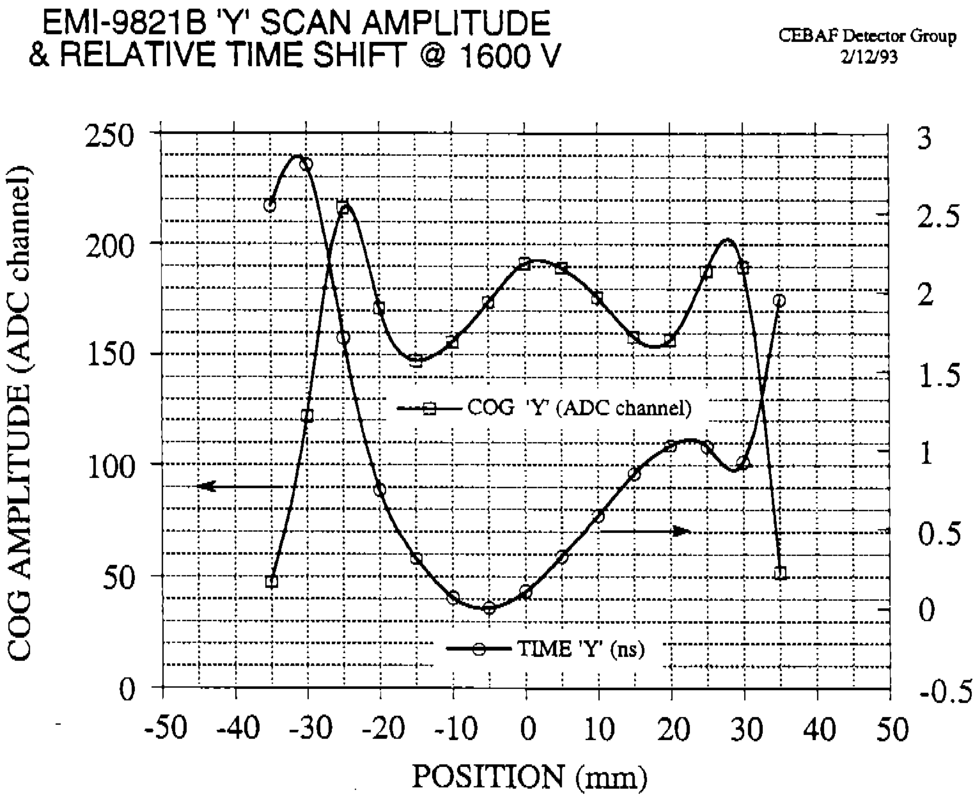
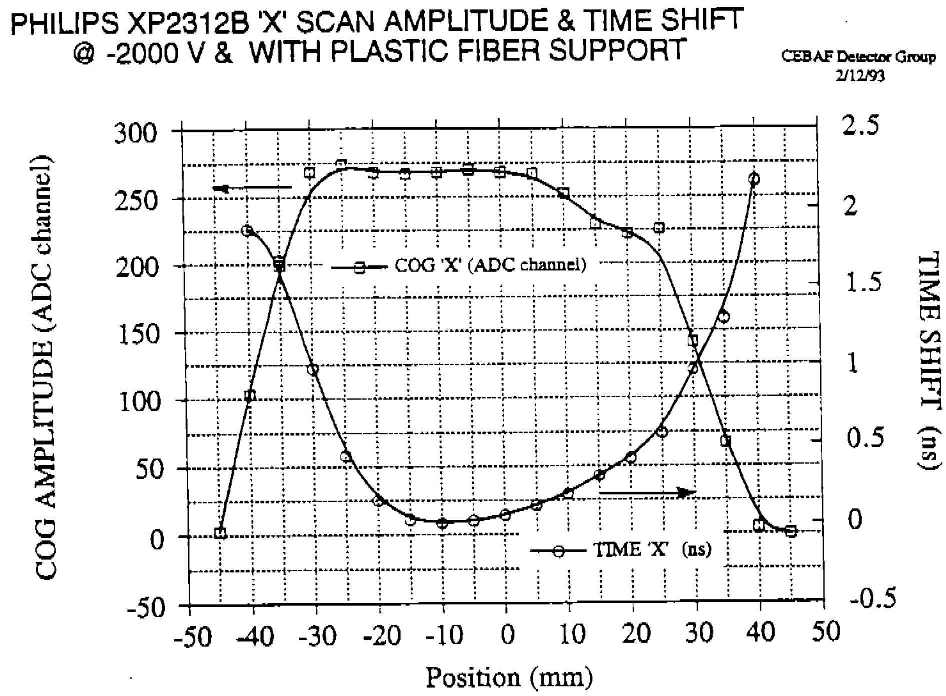


Figure 2: Transit time and pulse height variations for the Thorn EMI 9821B along a diameter of the 3" tube.



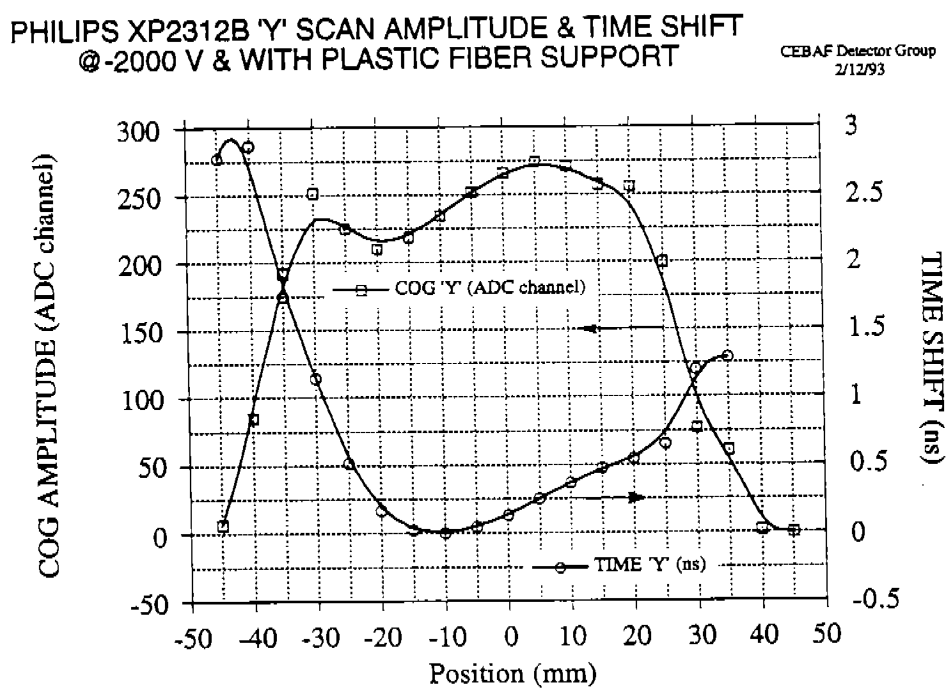
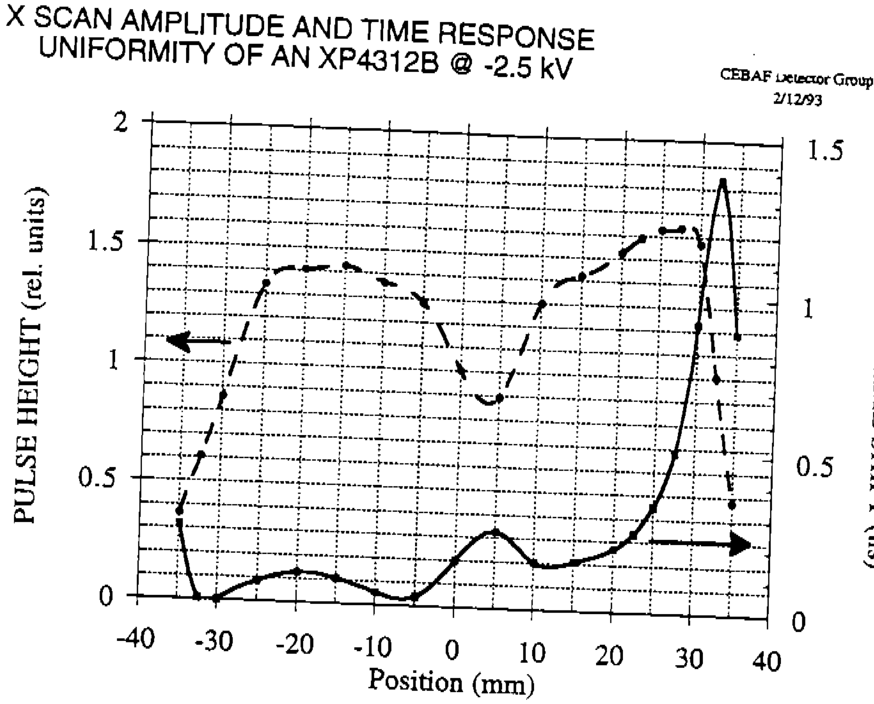


Figure 3: Transit time and pulse height variations for the Philips XP2312B along a diameter of the 3" tube.



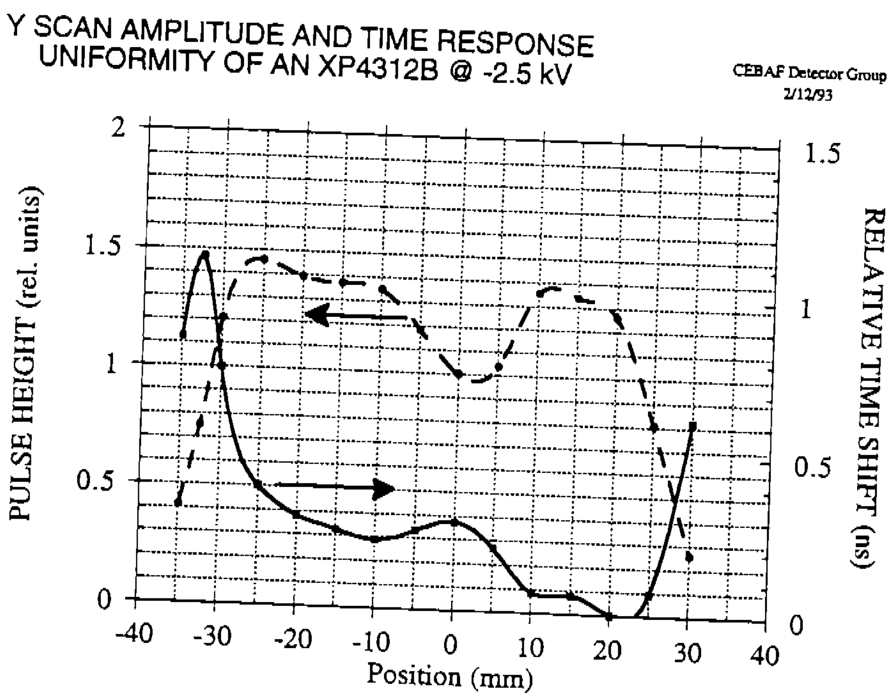
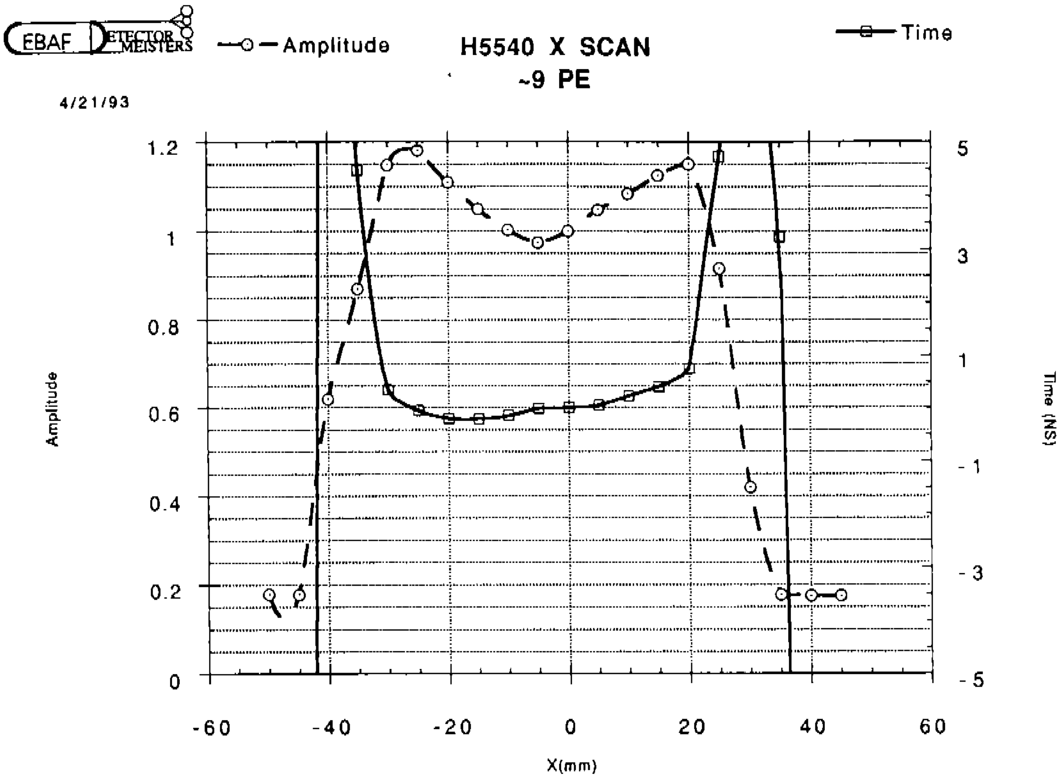


Figure 4: Transit time and pulse height variations for the Philips XP4312B/D1 along a diameter of the 3" tube.



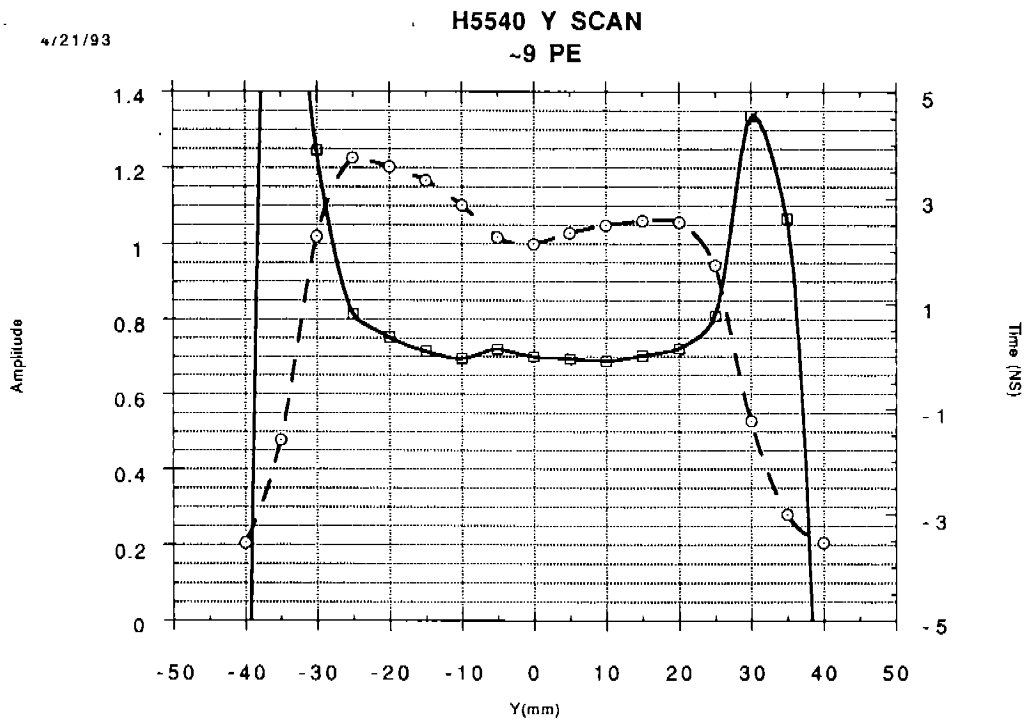


Figure 5: Transit time and pulse height variations for the Hamamatsu H5540 along a diameter of the 3" tube. This is the assembly for the R5004 PMT.

Plot Resolution vs Number Of Photoelectrons
3 inch Tube EMI 9821B

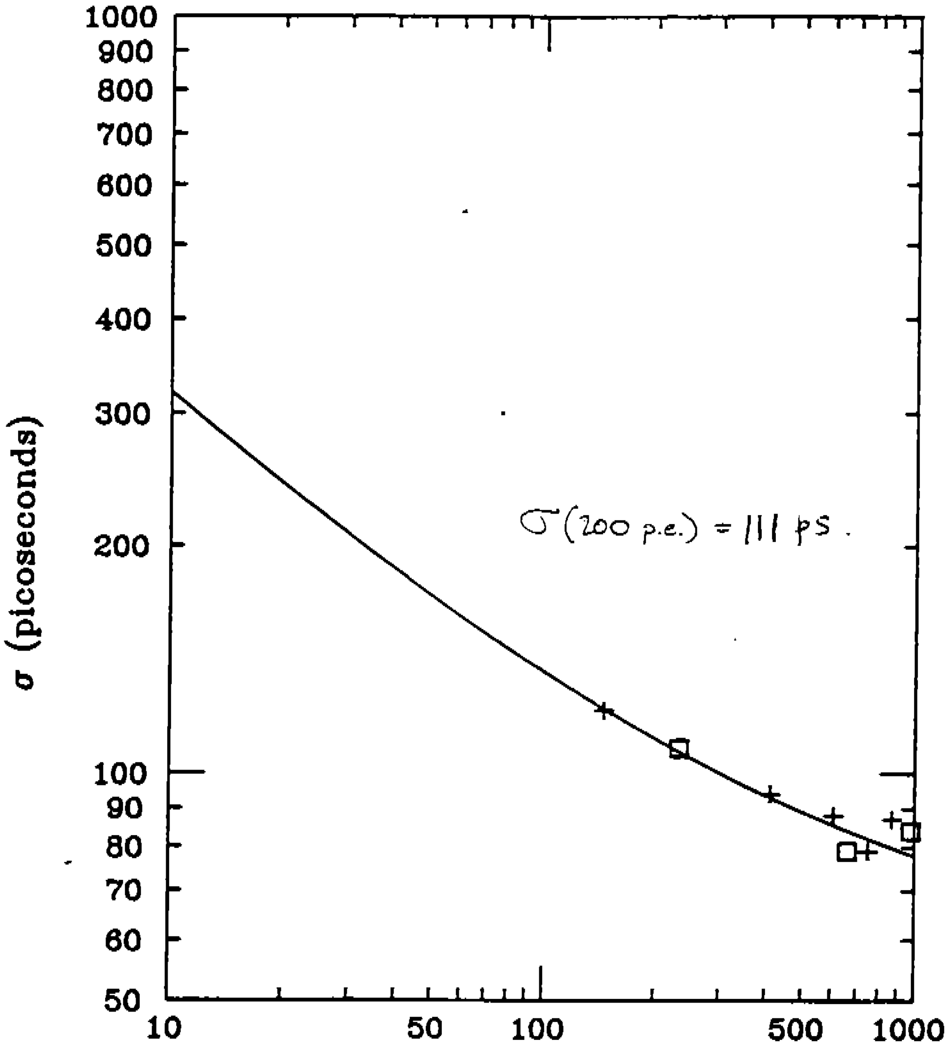


Figure 6: Time resolution for the Thorn EMI 9821B measured with nitrogen laser. The central 4 cm of the PMT was illuminated for this measurement.

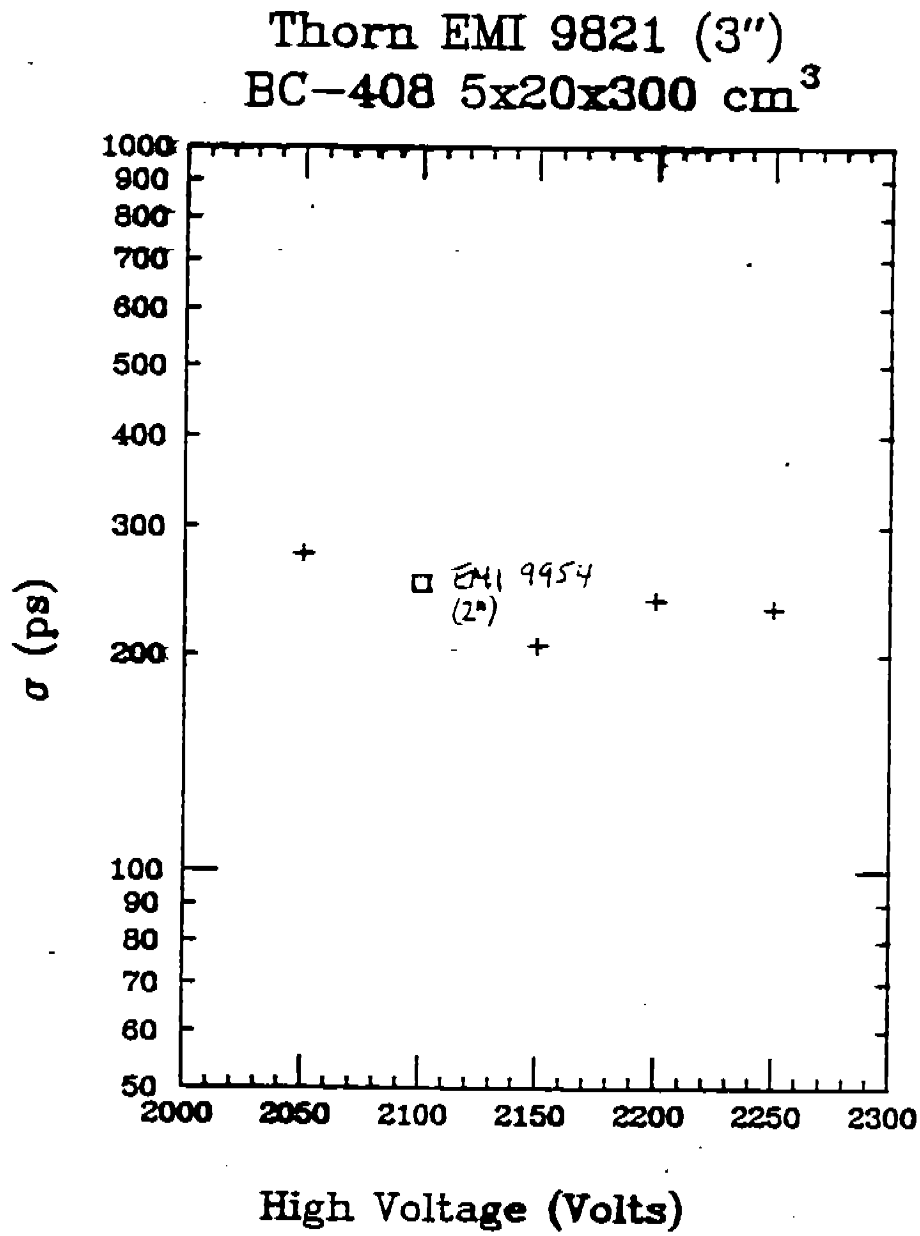


Figure 7: Time resolution for 9821B measured with cosmic rays. The scintillator used was a BC-408 with dimensions $300 \times 20 \times 5$ cm^3. One side of the scintillator was viewed by a 2" tube. The other end was attached first to the 3" 9821B, then to a 2" 9954B for reference. See text for details.

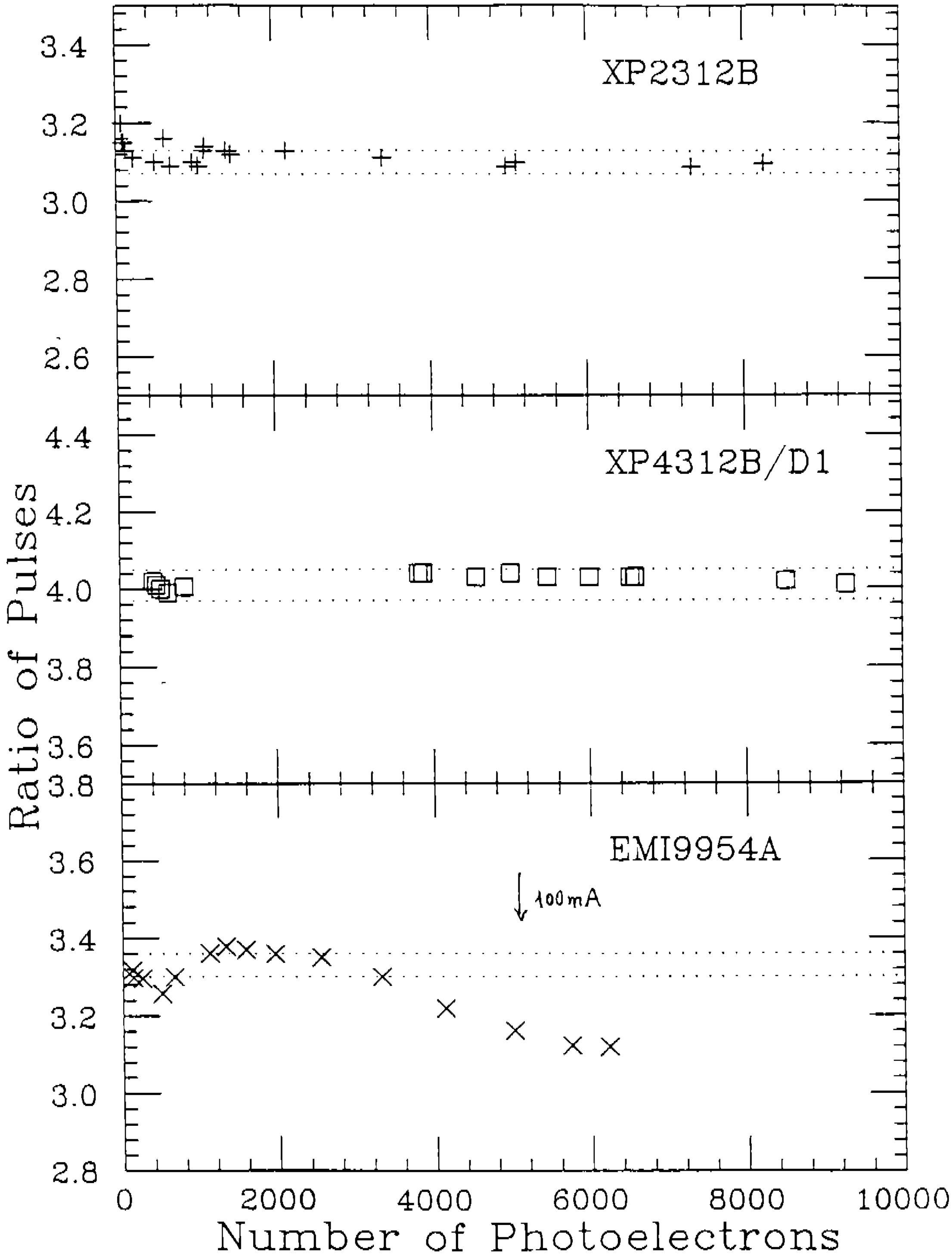


Figure 8: Linearity of XP2312B, XP4312B/D1 and EMI 9954A PMTs. The non-linearity of the PMT begins when the ratio deviates from its original value. Systematic difficulties covering the entire dynamic range lead to the slight mismatch at 800 photoelectrons. The bands indicate a ±1% deviations.

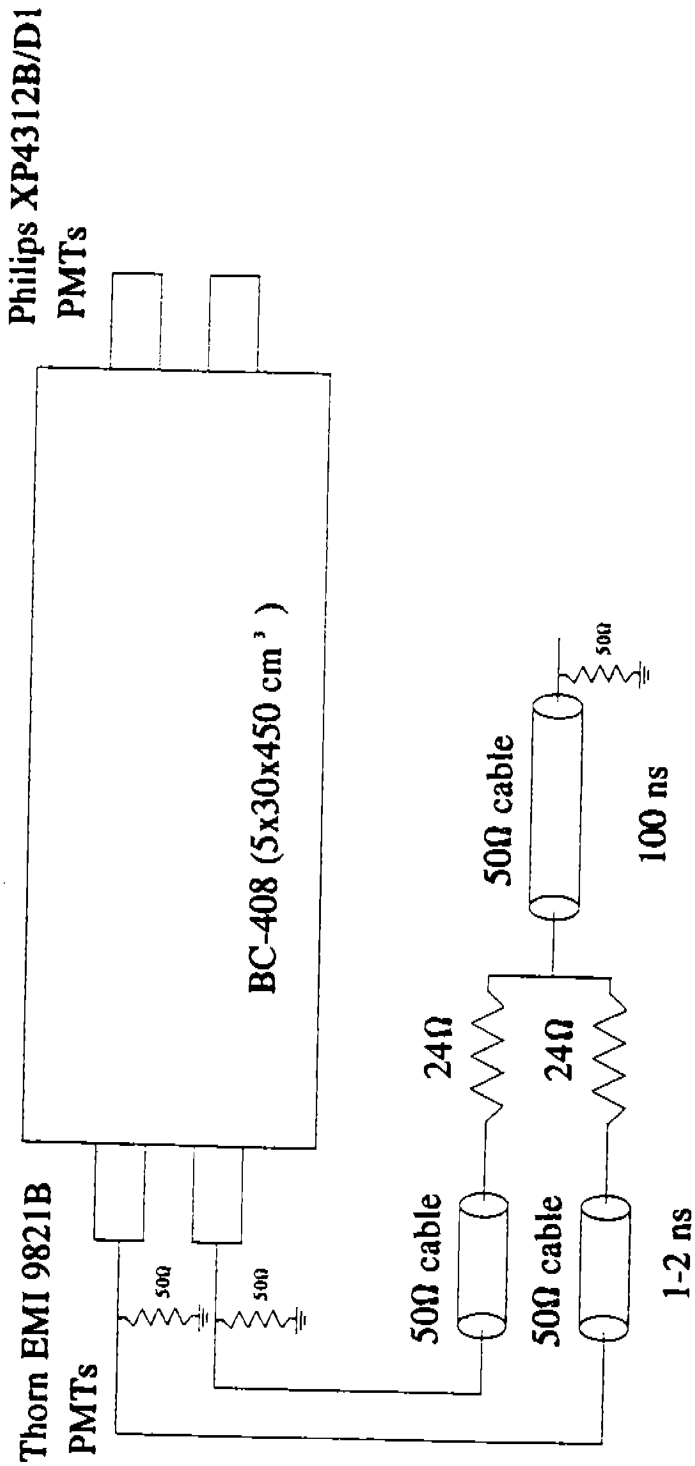


Figure 9: Setup for double PMT tests. For clarity, the 50Ω terminations are shown explicitly. However, they were usually internal to either the voltage divider or NIM electronics.

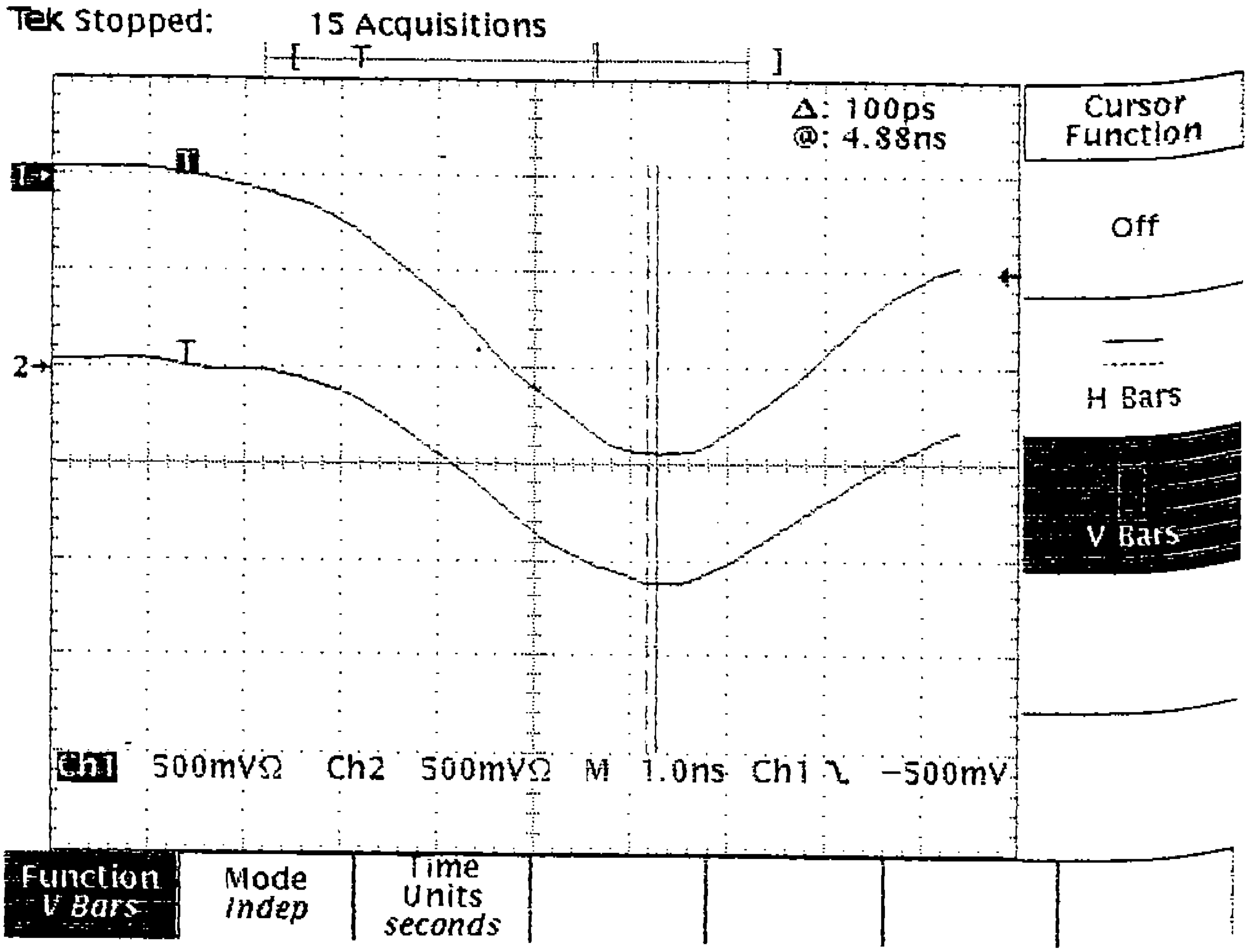


Figure 10: Oscilloscope traces showing the time alignment of two PMTs using the Tektronics TDS640 oscilloscope. We estimate that we can set the relative times in this way to within 200 ps.

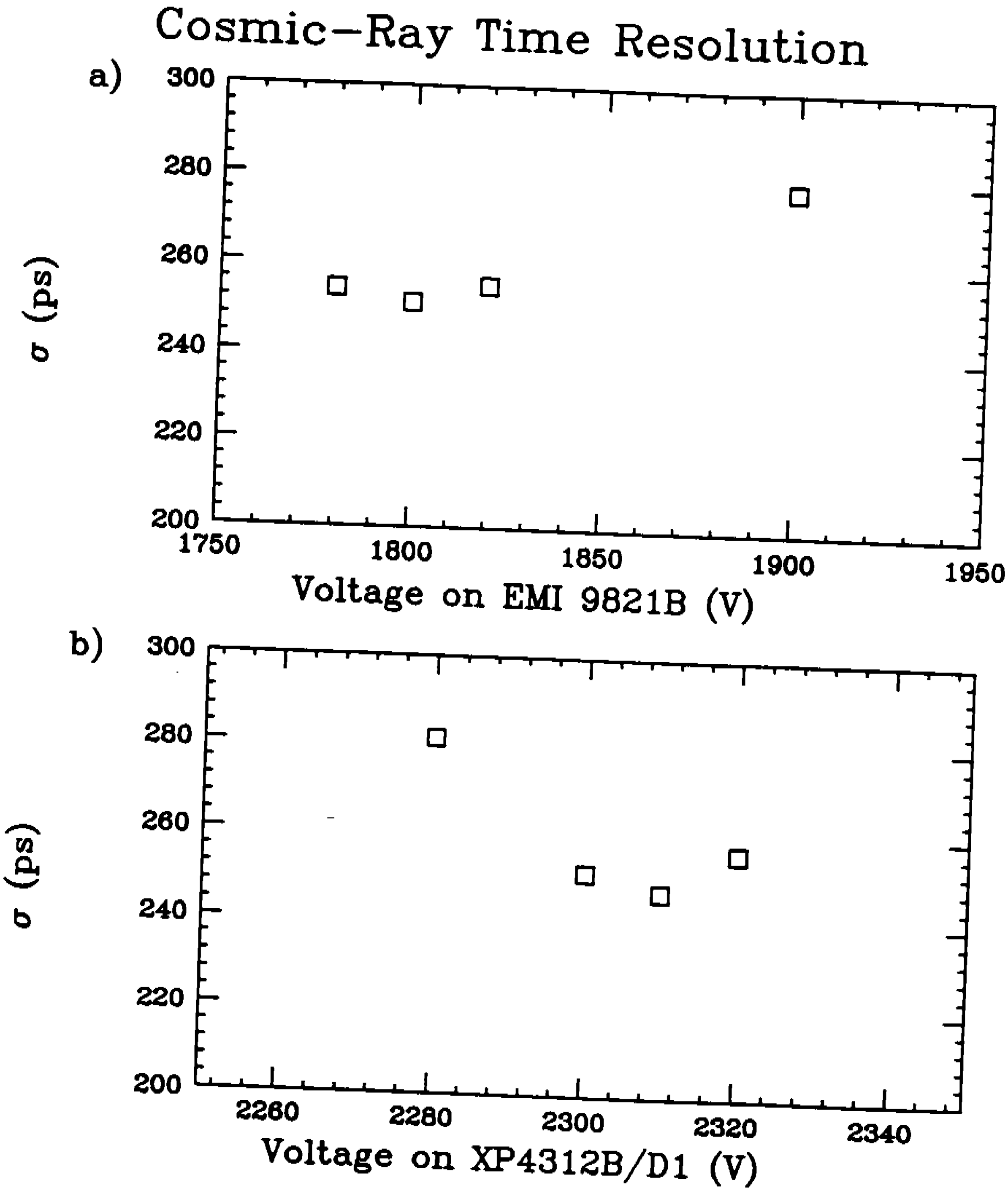


Figure 11: Time resolution variation as a function of HV on two of the four tubes. The resolution is relatively insensitive to changes in HV. The systematic error in the measurements is about 5%.

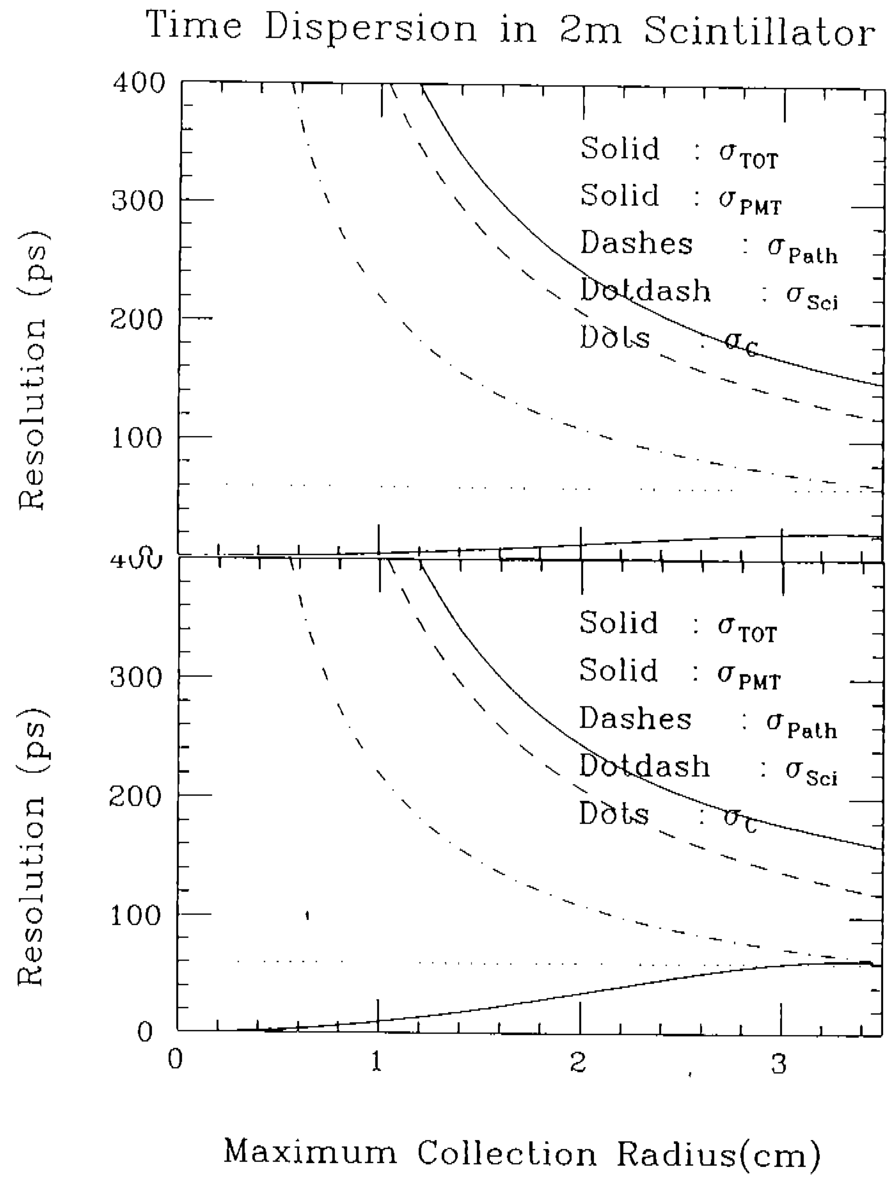


Figure 12: The components to the time resolution given in Equation (1) are plotted as a function of the PMT radius. The intrinsic PMT resolution degrades for larger radii, but the increased acceptance improves the overall time resolution. The top plot is for σ_{PMT}=320 ps, the bottom for σ_{PMT}=880 ps.