Optimization of TOFPET Detectors

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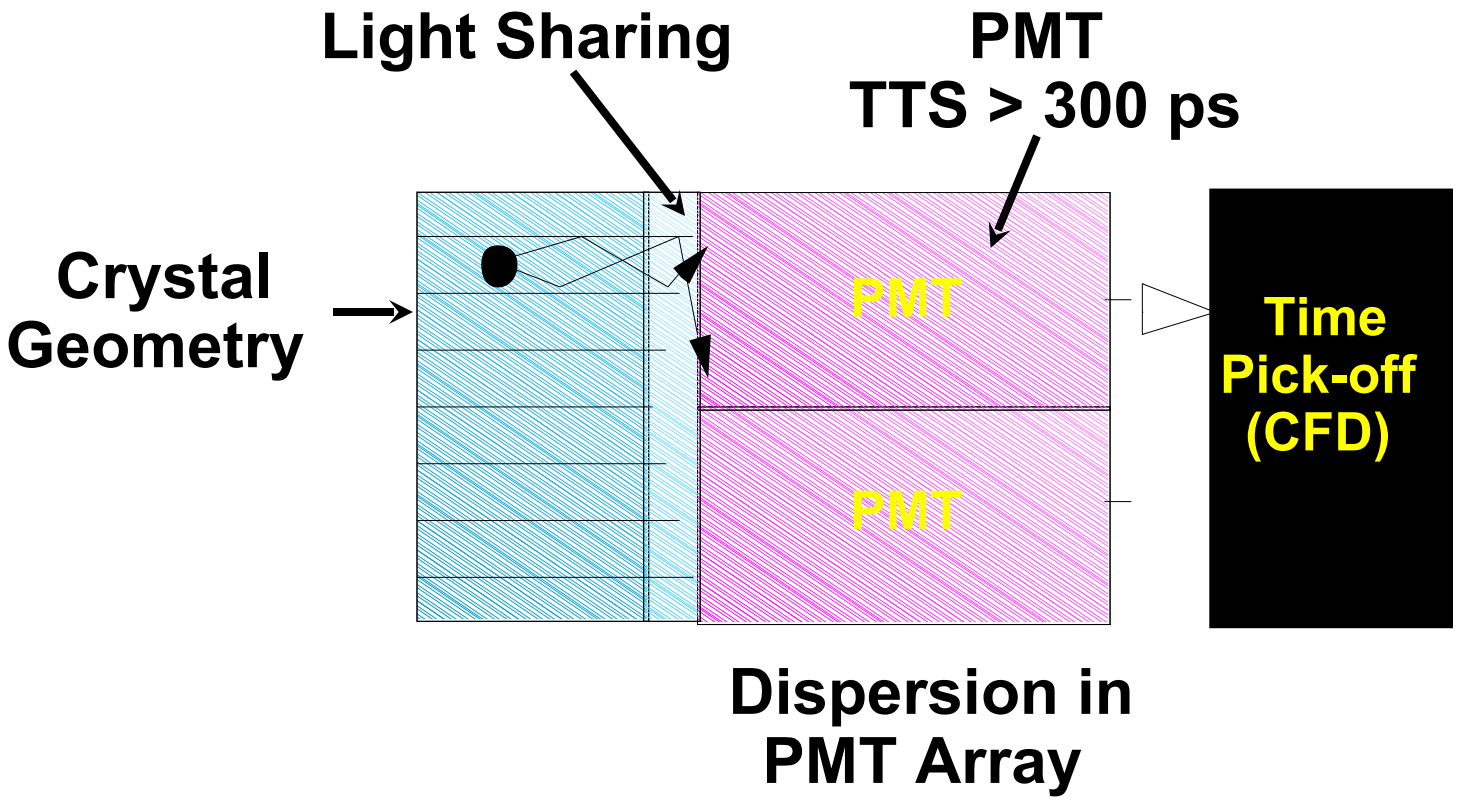
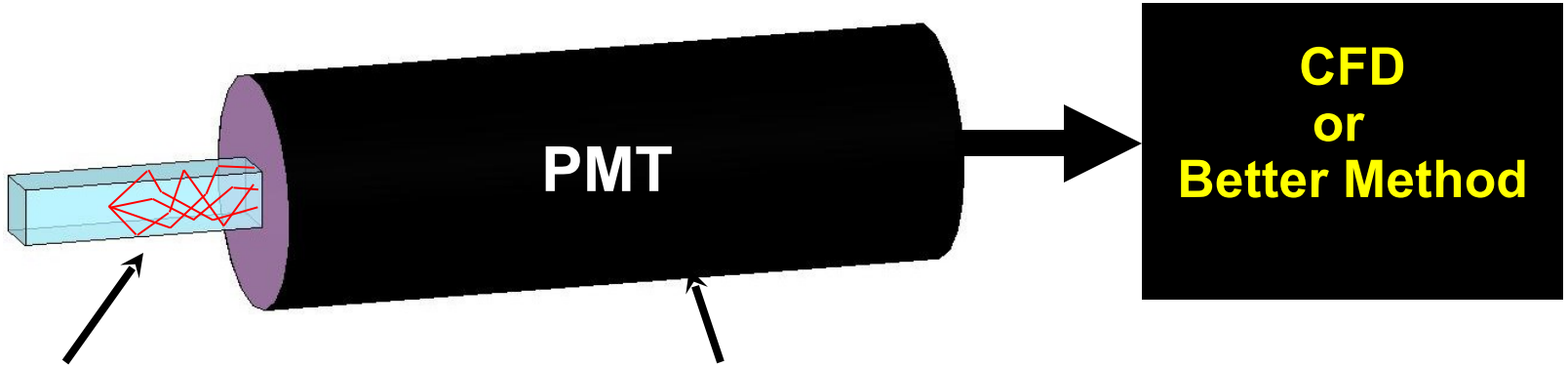
Question:

Can we build a PET detector module with a timing resolution of 100 ps FWHM with current technology?

Time Dispersion in Block Detector



What is the Ideal Scintillation Detector for Timing?



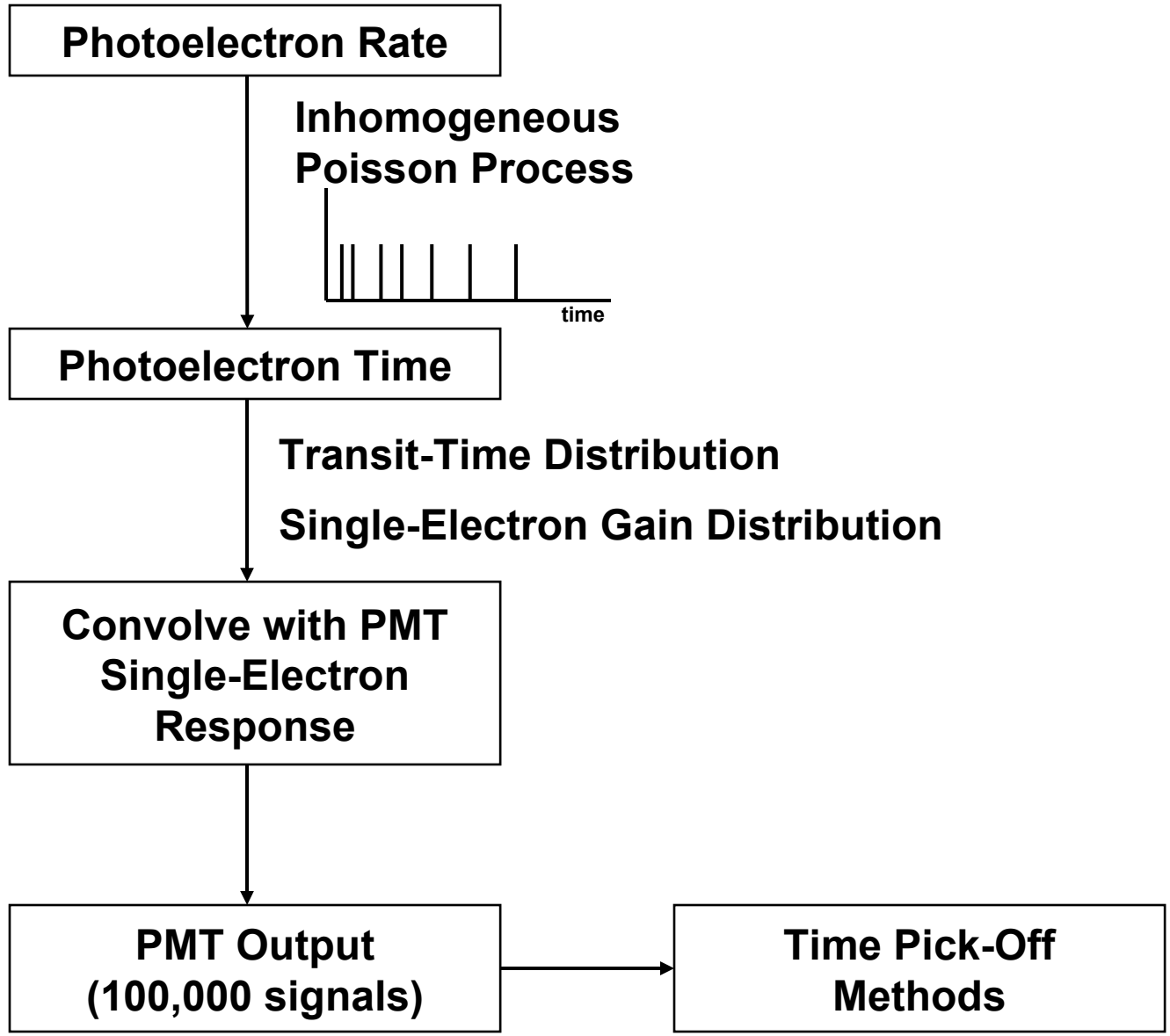
Direct 1-to-1 coupling of short crystal to photodetector

PMT with high PDE and low TTS

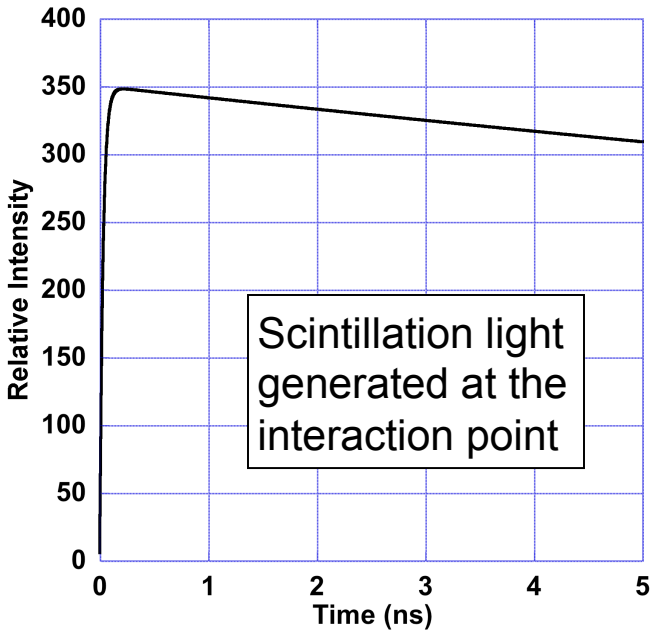
Requirements For PET Detectors:

- High detection efficiency (high stopping power for 511 keV).
- Able to tile detector modules together with minimum dead area.

Monte Carlo Analysis of Timing Resolution

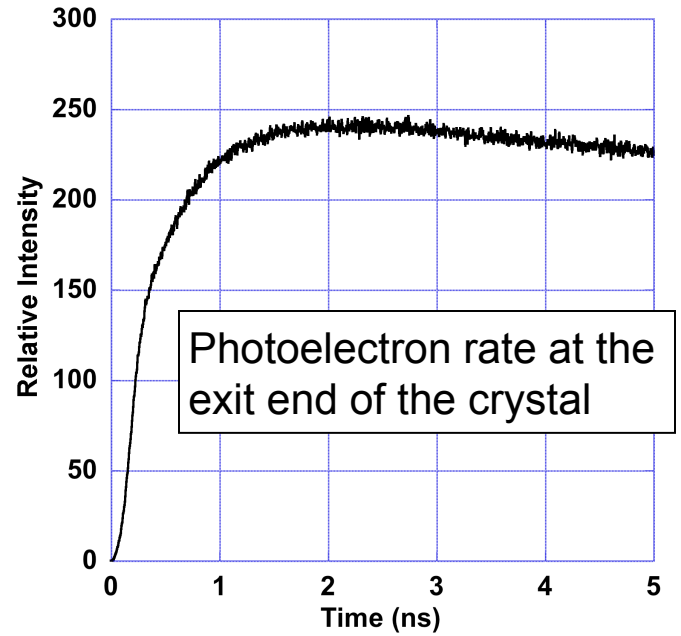


Modeling Photoelectron Rate Function



Light transport using Geant4

Average over all interaction depth given by $\exp(z/\lambda_L)\lambda_L = 12$ mm



$$\frac{I_0}{t_d - t_r}\left[e^{-t/t_d} - e^{-t/t_r}\right]$$

For LSO: $\tau_r = 0.030$ ns, $\tau_d = 40$ ns

The total area under the curve is normalized to the mean photoelectron yield:

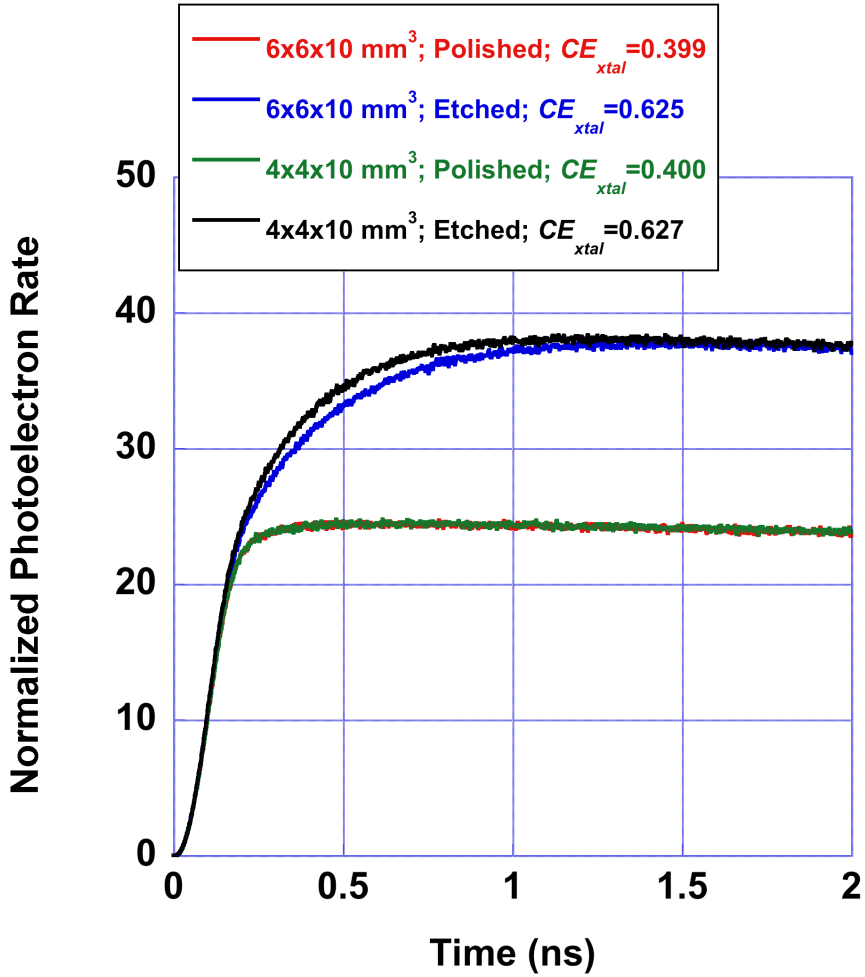
$$I_0 = L\,L\,QE_{PMT}\,P\,CE_{xtal}$$

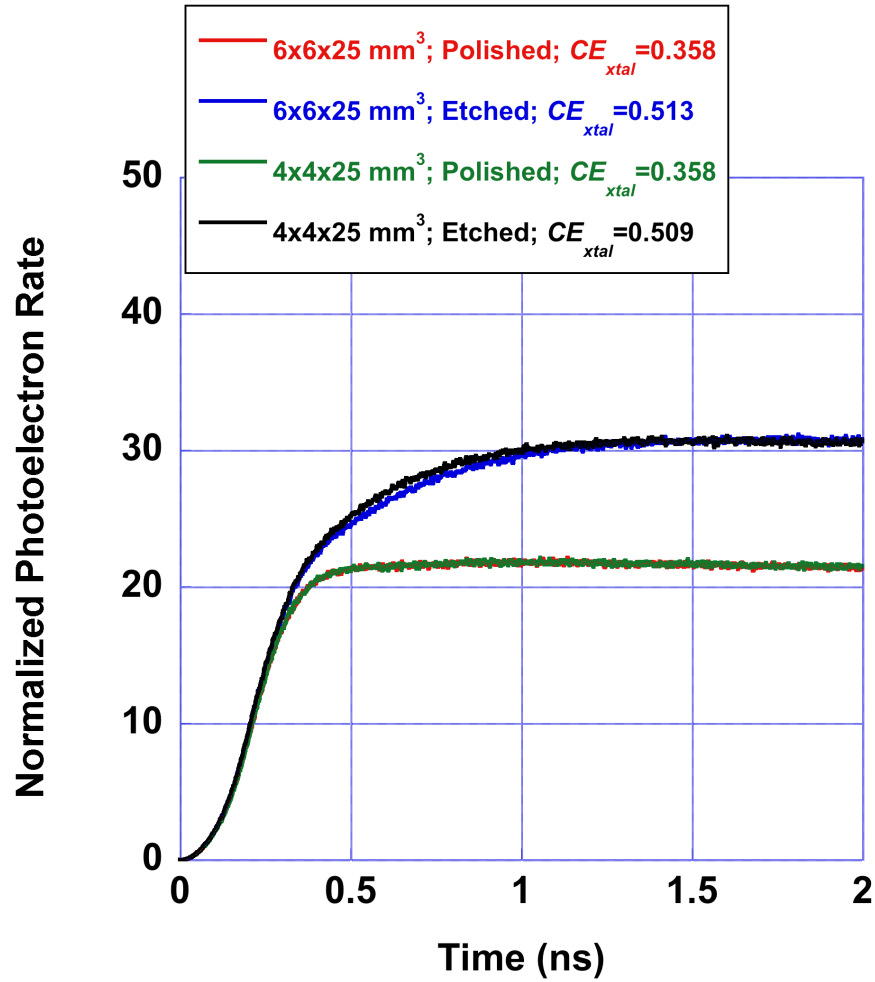
$L \sim$ 25000 photons/MeV x 0.511

QE_{PMT} =0.20

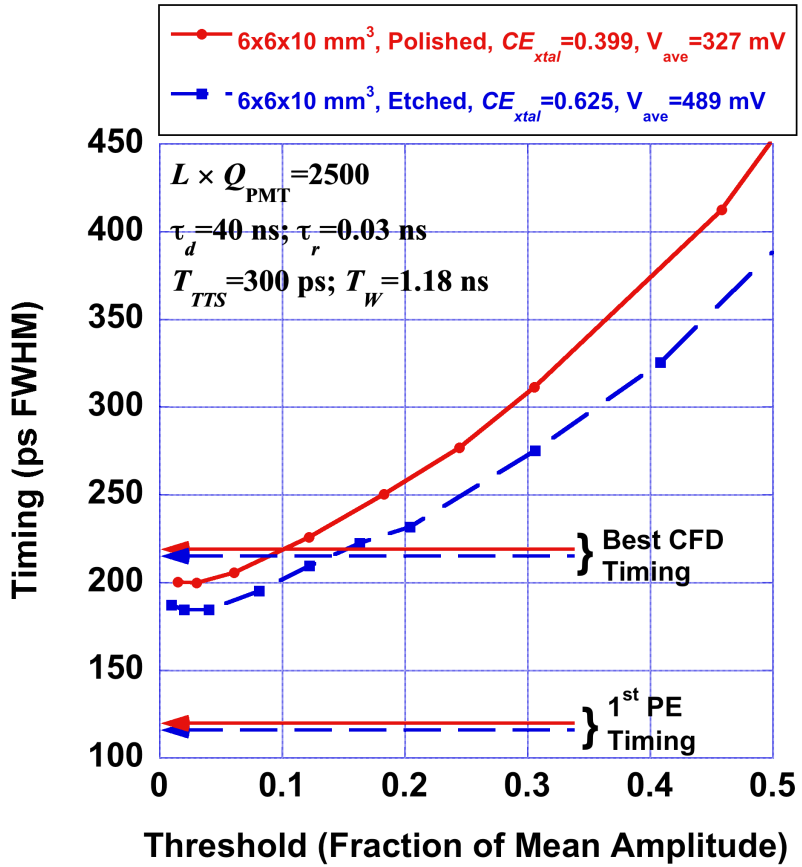
CE_{xtal} = 0.4 to 0.7

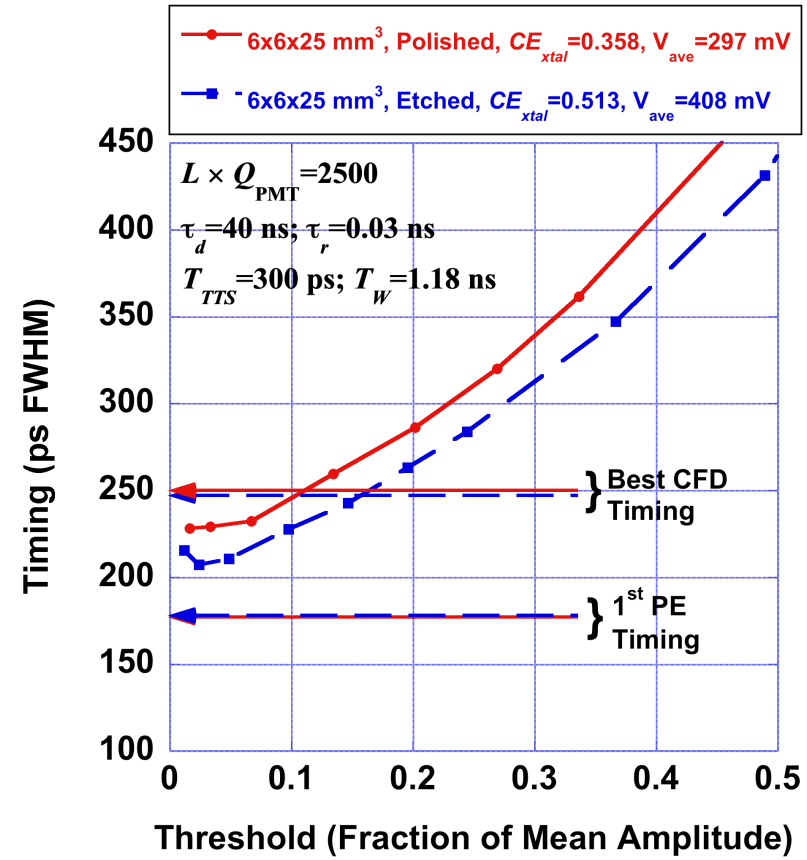
Some Simulated Photoelectron Rate Function





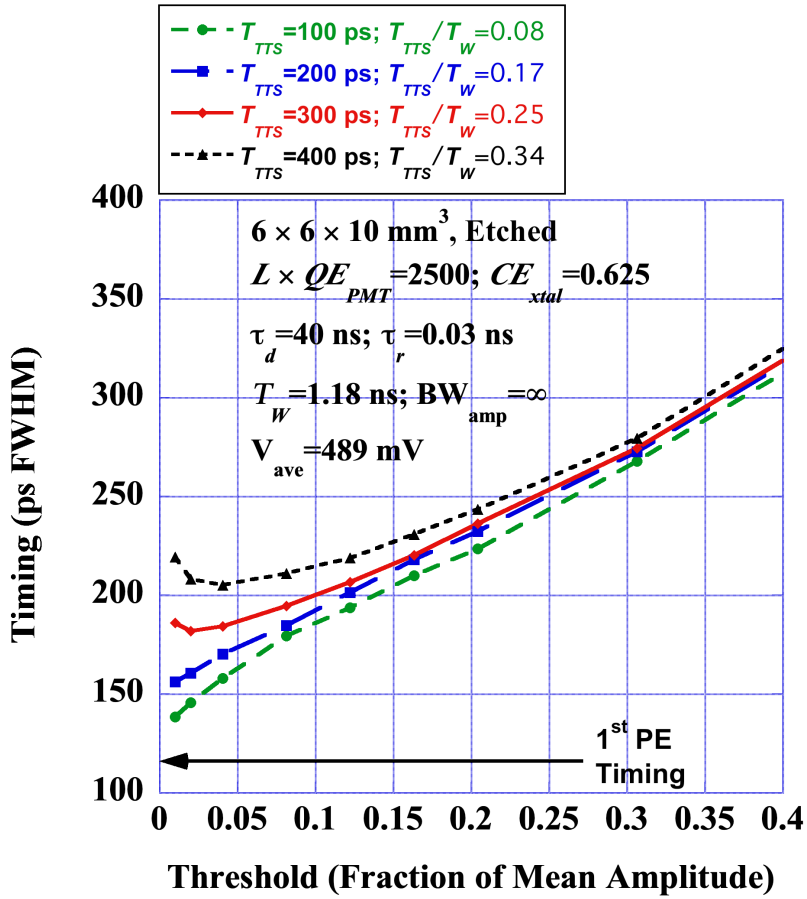
Dependence of Timing on Time Pick-Off Methods

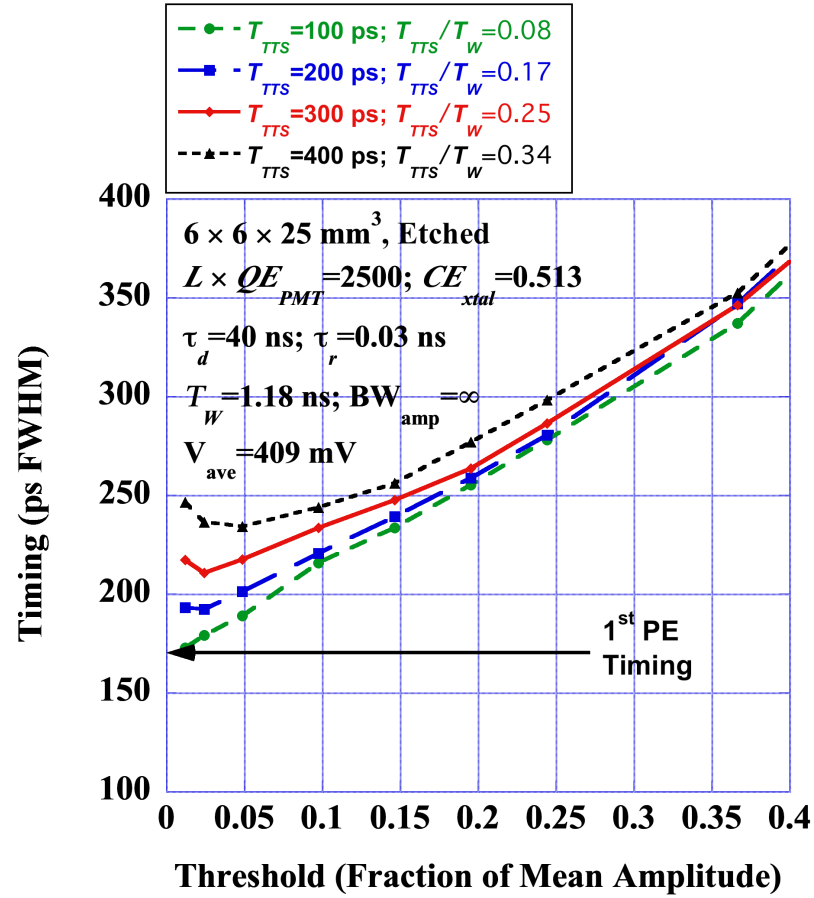




- 1 PE timing gives the statistical limit based photoelectron rate.
- LE performs better than CFD at the optimum threshold. This behavior is consistent with Hyman theory and has been experimentally verified by us and other groups.

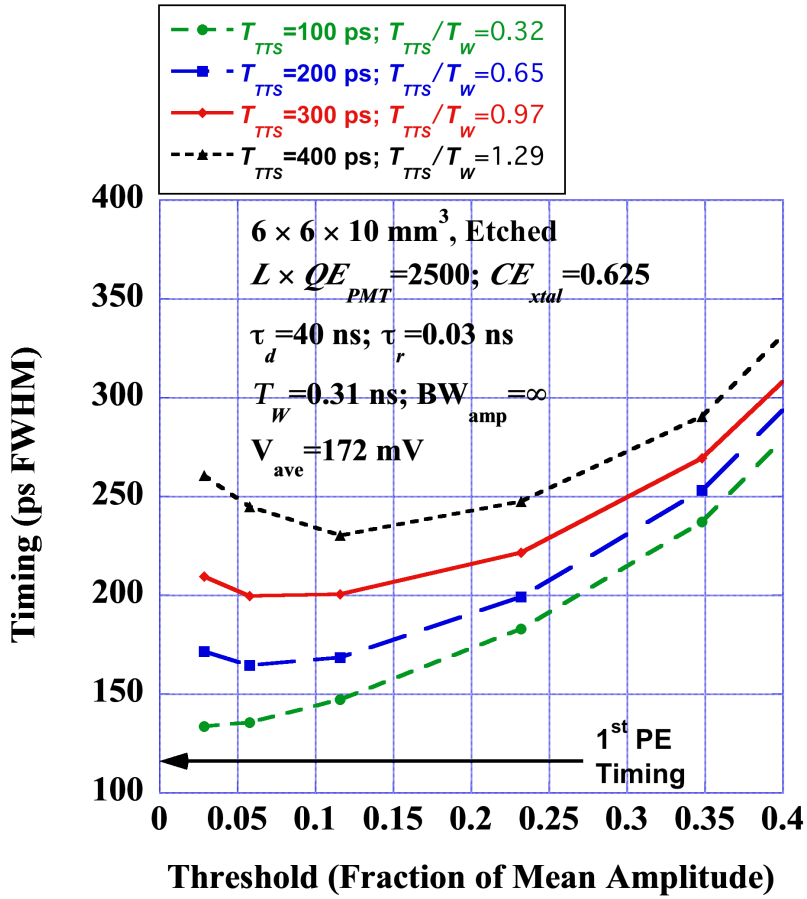
Dependence of Timing on TTS (T_w=1.18 ns)

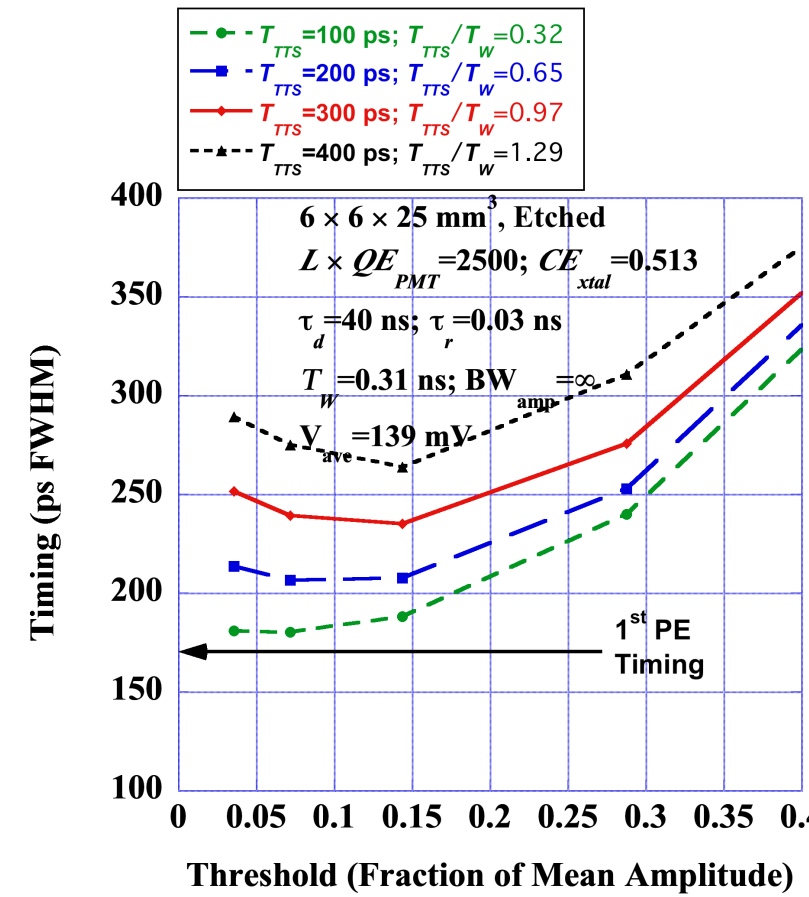




- **More gain in timing with improved TTS for 1 PE < TTS.**
- **For *TW*>>TTS => best timing is achieved with lowest LE threshold.**

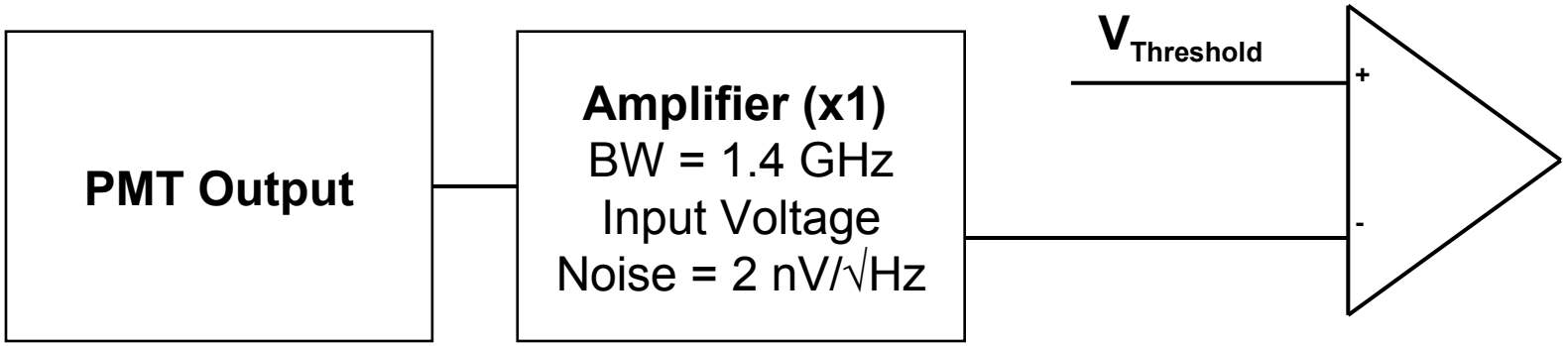
Dependence of Timing on TTS (T_w=0.31 ns)





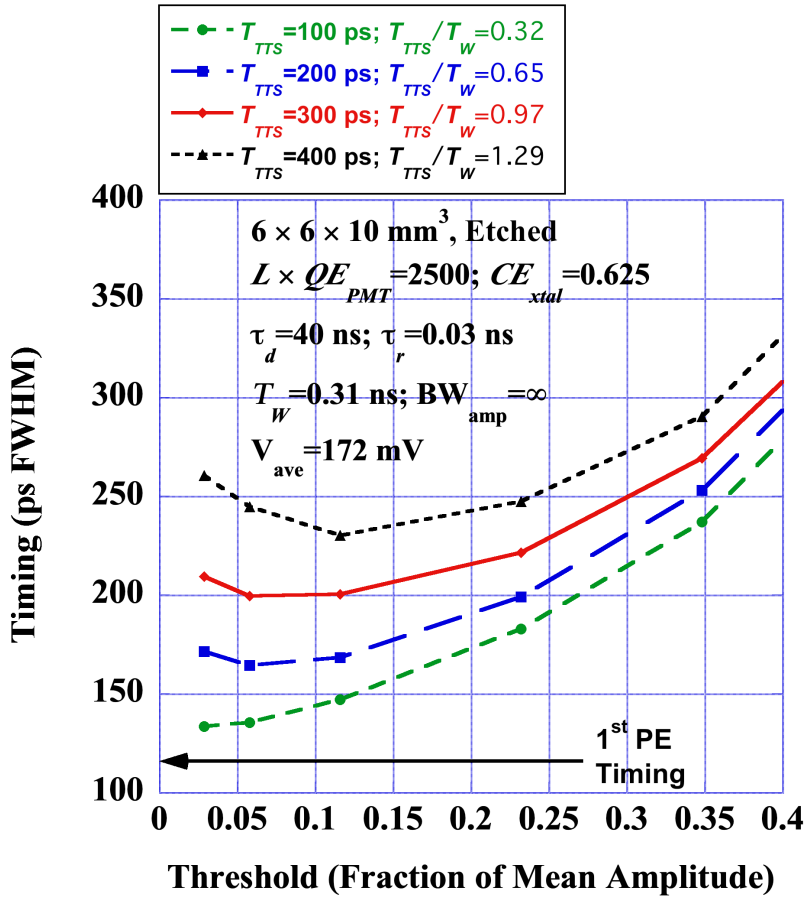
- **Faster SER gives the best timing at higher LE threshold.**
- **At high TTS, timing is worse than for slower SER (higher amplitude).**

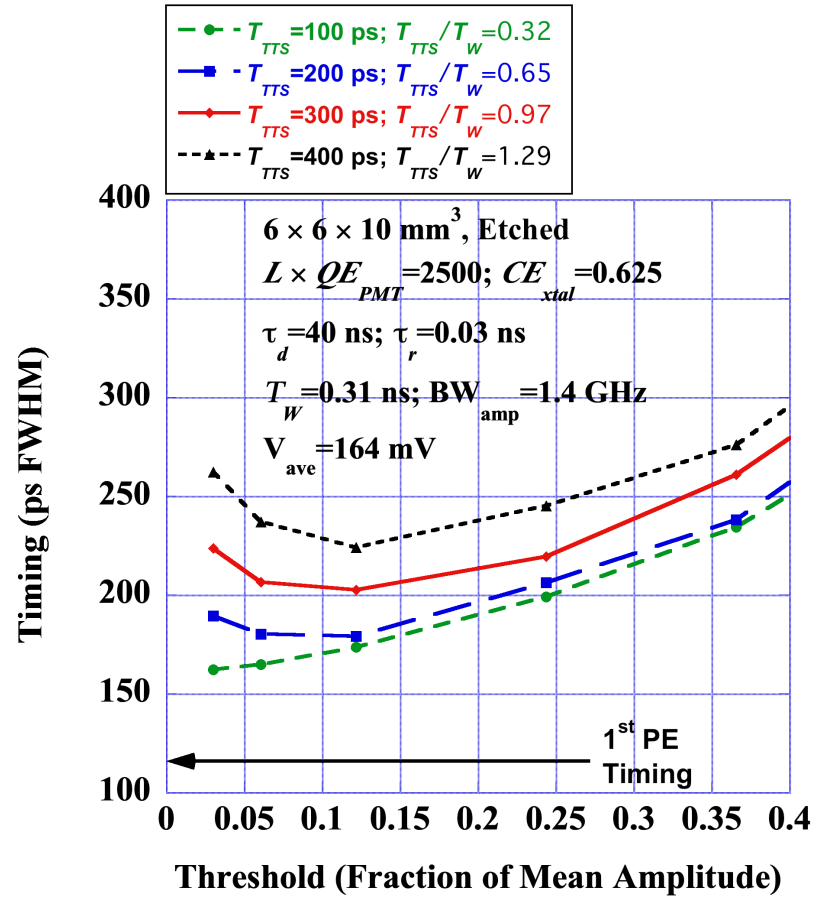
Modeling The Amplifier Bandwidth



- **FFT the PMT output signal.**
- **Apply the bandwidth cutoff in frequency space.**
- **Inverse FFT to get the amplified signal.**

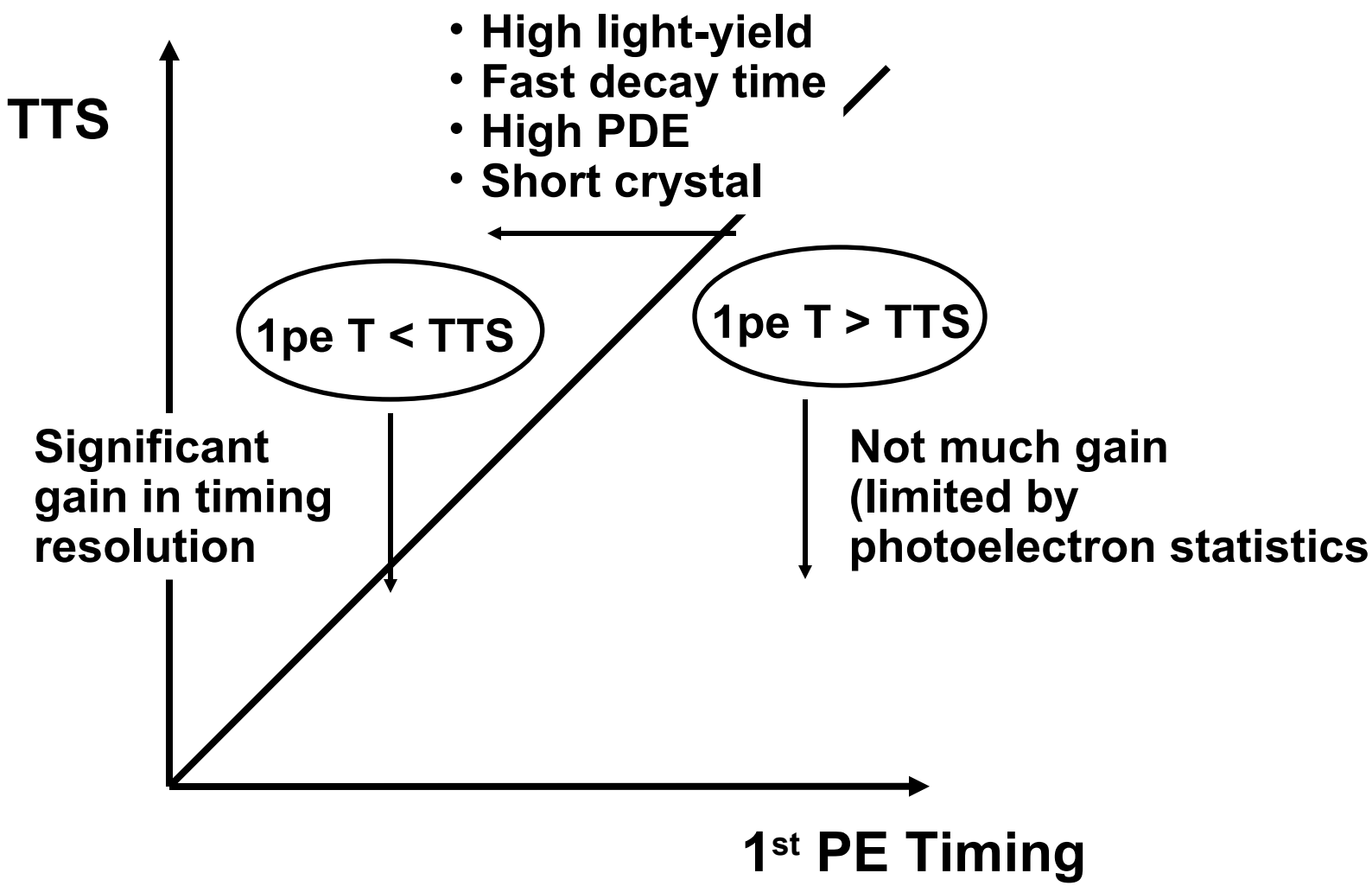
Dependence of Timing on BW of the Amplifier



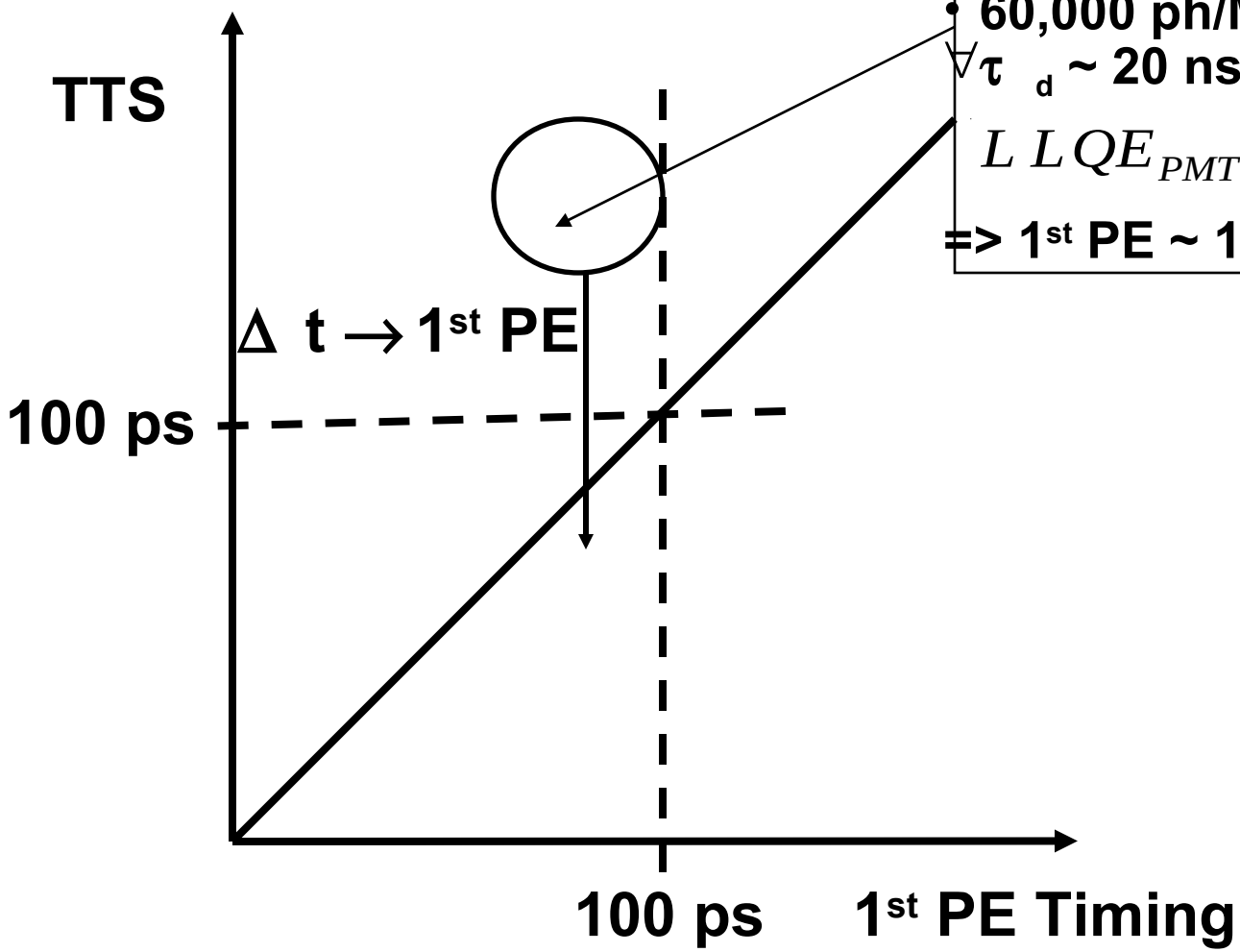


- Timing degrades if amplifier BW is limited (assuming no noise).
- Higher BW => Higher noise => Might not improve timing.

Summary


• High light-yield
• Fast decay time
• High PDE
• Short crystal
TTS
1pe T < TTS
1pe T > TTS
Significant gain in timing resolution
Not much gain (limited by photoelectron statistics
1st PE Timing

Implications: $LaBr_3$



LaBr3 (Δ t > 1 T):

- 60,000 ph/MeV

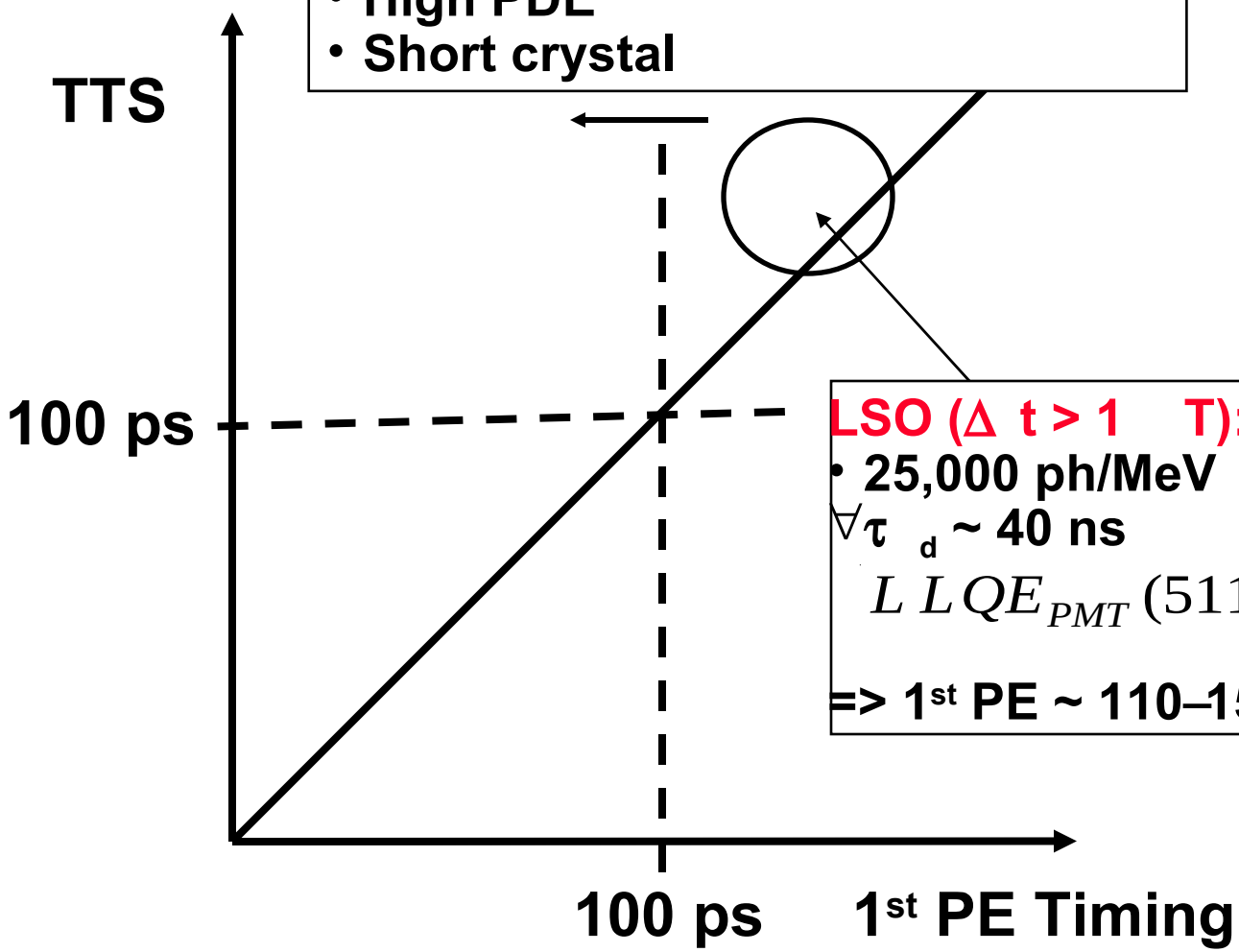
∀τ d ~ 20 ns

$$L\,LQE_{PMT}(511keV) > 5000$$

=> 1st PE ~ 100 ps for L<20 mm

Implications: LSO

- Fast LSO (co-doped Ca): 10–20% more light, τ_d ~ 30 ns
- High PDE
- Short crystal



LSO ($\Delta t > 1$ T):

- 25,000 ph/MeV

$\forall \tau_d$ ~ 40 ns

$$L\,LQE_{PMT}(511keV) \sim 2500$$

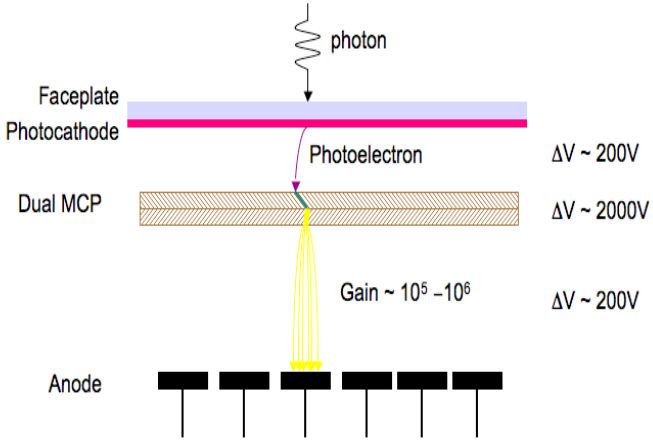
=> 1st PE ~ 110–150 ps for L<20 mm

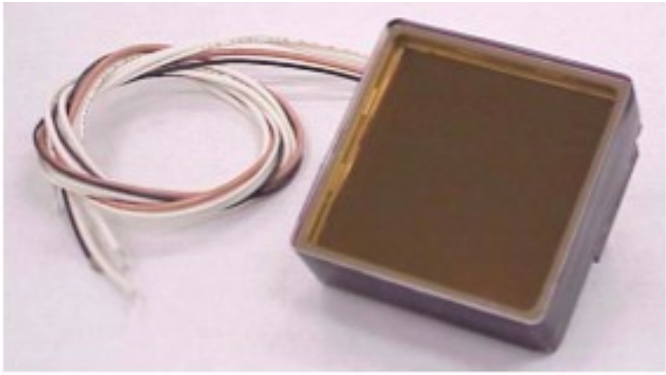
Parameters of Promising PMTs

PMT	Type of PMT	Size [mm]	Cathode Blue Sensitivity [μ A/lmF]	Measured TTS [ps FWHM]
R5320	Dynode	∅ 25	9.0	159
R9800	Dynode	∅ 25	~11	262
R9800 (SBA)	Dynode	∅ 25	~13	
XP20D0	Dynode	∅ 51	12.7	510
85011-501	MCP (25 μ m)	51× 51	8.0	140 to 156
85015/A1	MCP (10 μ m)	51× 51	8.5	75 to 80

*** Another new promising photodetector: SiPM (TTS ~ 100–200 ps FWHM)**

Multi-anode MCP PMT



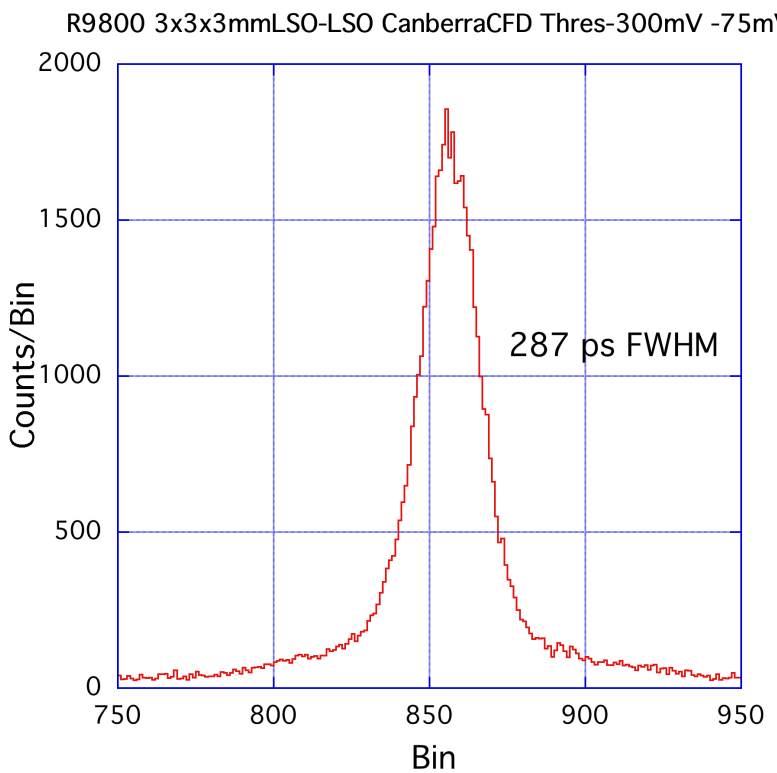


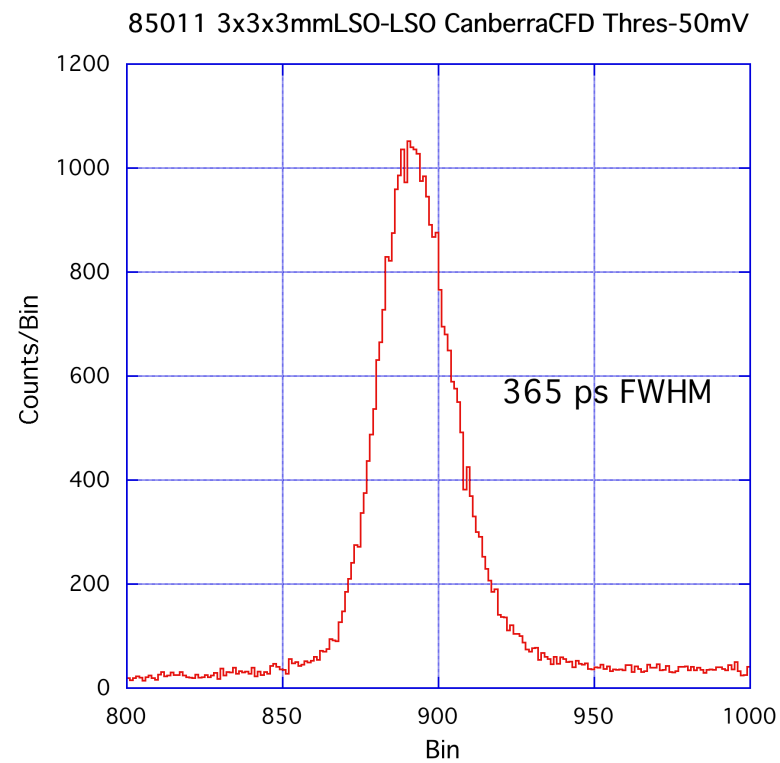
Photonis Planacon

Parameter	85011	New Tube
Photocathode	Bialkali	Bialkali
Number of MCPs	2	2
Pore size (μ m)	25	10
Blue sensitivity index	8.0	8.5
Open area ratio	66%	80%
Active area (mm)	51× 51	51× 51
Anodes	8× 8	8× 8

- **Multi-anode => permit direct 1-to-1 coupling of crystal.**
- **Excellent TTS**
- **Fast SER**

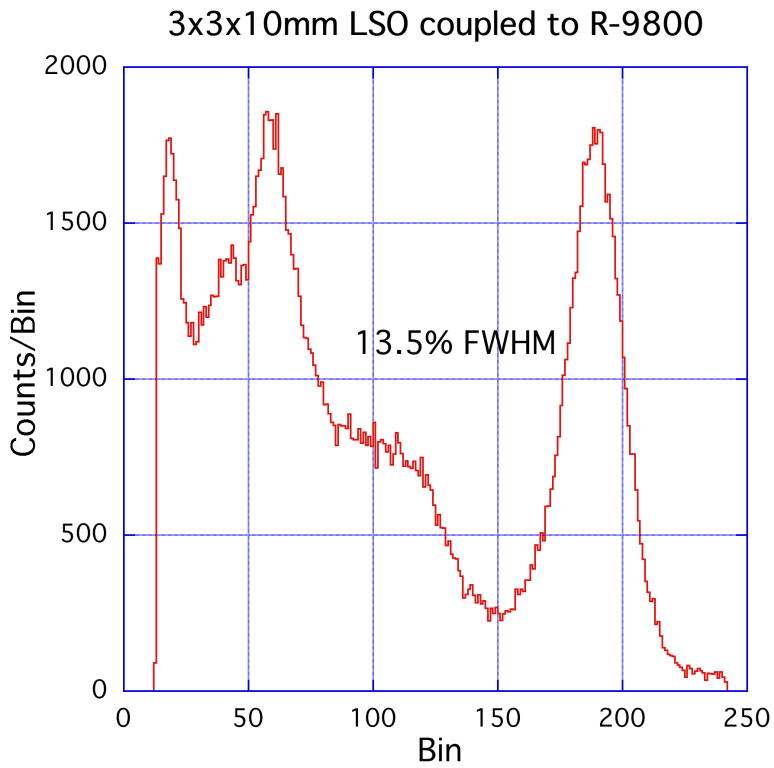
Measured Timing Resolution

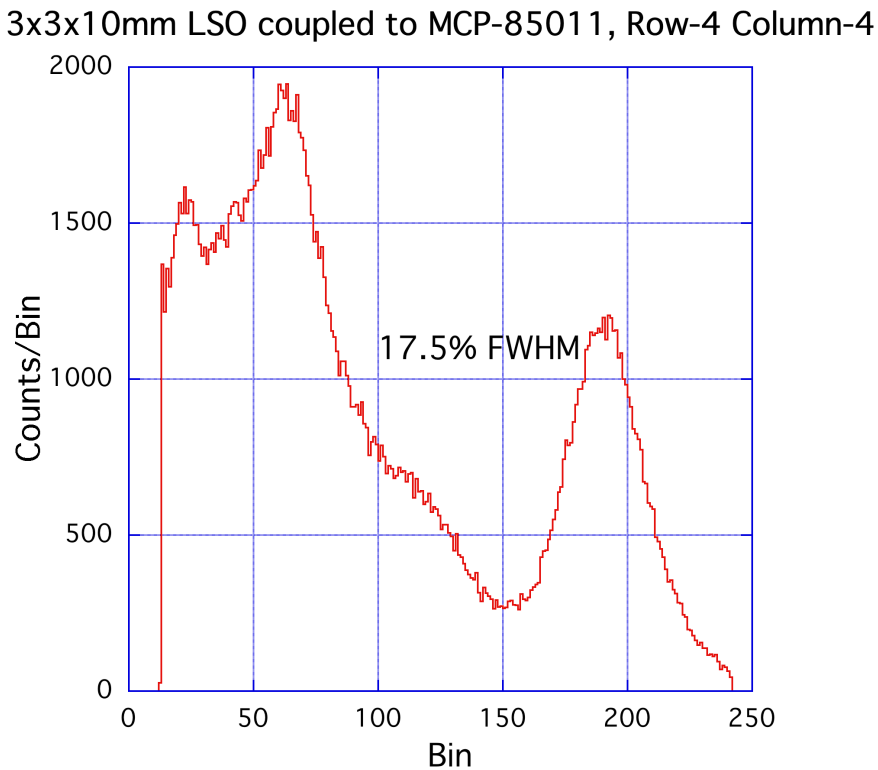




Timing resolution of reference detector ~ 150 ps FWHM

Measured Energy Resolution





Conclusion

- Low LE threshold performs better than CFD.
- More gain in timing resolution with improved TTS if 1st PE timing is less than TTS. Just low TTS alone is not sufficient if limited by the statistics of the initial photoelectron rate.
- Fast SER permit higher LE threshold to achieve optimum timing resolution at low TTS. However, higher bandwidth amplifier might be required.
- For $LaBr_3$: timing resolution ~ 100 ps FWHM is possible (but low detection efficiency).
- For LSO: more development is needed to achieve timing resoluiotn ~ 100 ps FWHM -- high QE photocathode (35–40% is possible), co-doped with Ca (higher light output, faster decay time).