PMT EVALUATION FOR THE DAYA BAY NEUTRINO EXPERIMENT

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Neutrinos

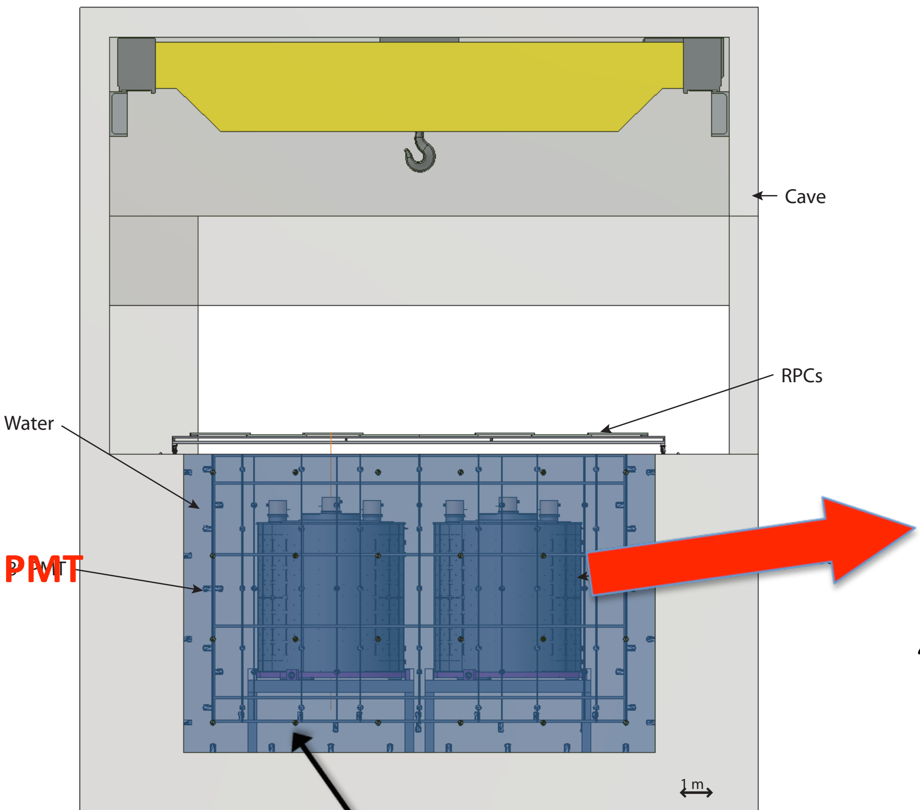
- Neutrinos produced and detected as flavor eigenstates, propagate as mass eigenstates => neutrino oscillation.

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

- Mixing angles: $\theta_{12} \sim 38^\circ$, $\theta_{23} \sim 45^\circ$, **$\theta_{13}$ ~ unknown.**
- Importance of θ_{13}.
  - Key element of mixing matrix.
  - Gateway to the CP violation in neutrino sector.
  - Value is important in designing next generation experiment to measure δ_{CP}.
- Daya Bay experiment will determine $\sin^2(2\theta_{13})$ with a sensitivity better than 0.01.

Daya Bay (DYB) Experiment

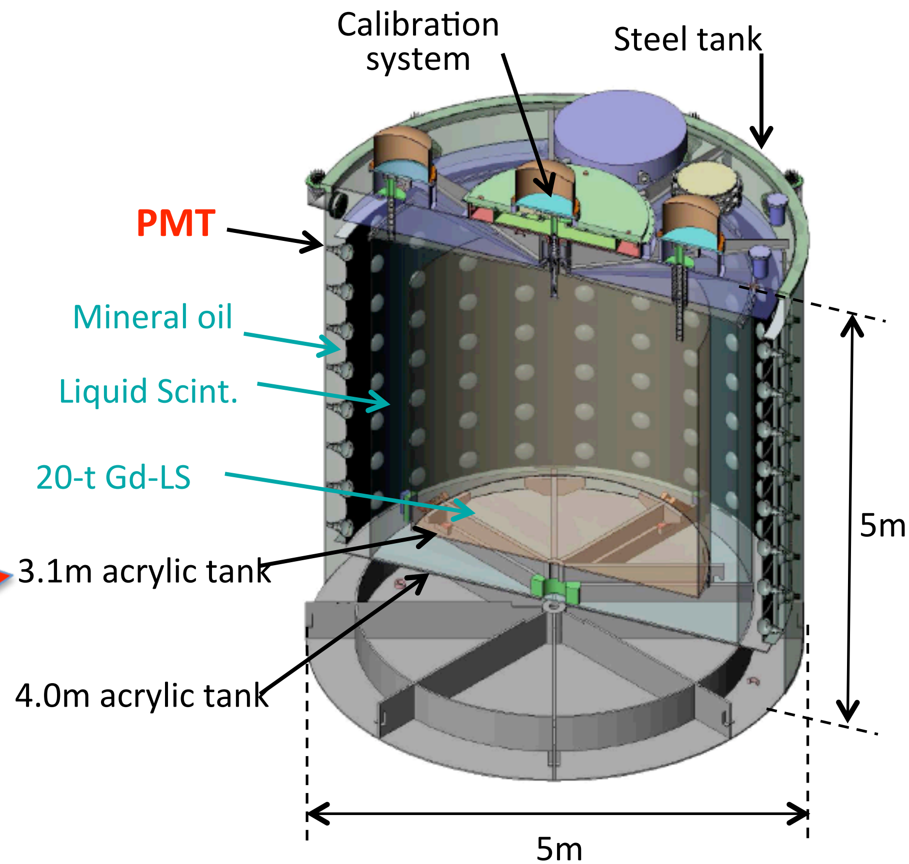
Experimental Hall



Water Cherenkov Detector

Total number of PMTs needed: ~2500

Anti-neutrino Detector



- For AD: 192 Low background 8" PMTs
- Energy resolution:
  - $\sigma_E/E = 12\%/\sqrt{E}$.

DYB PMT Requirements

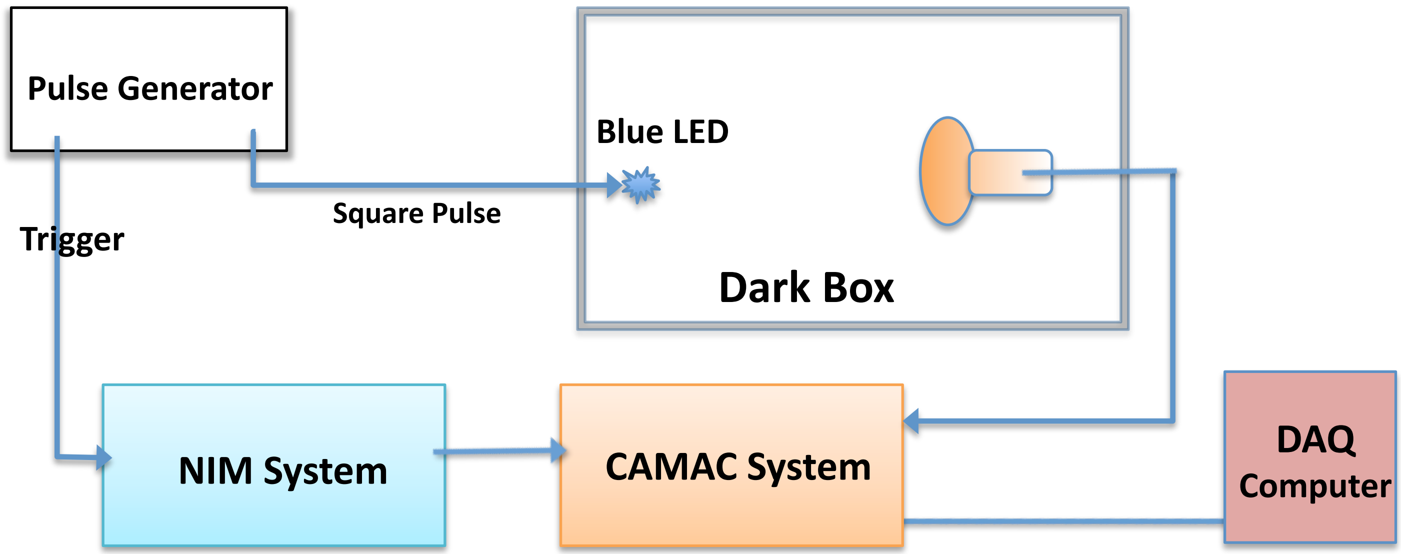
	DYB Requirement	
Peak to valley ratio	> 2.5	SPE @ gain=10^7
Gain @ $3x10^7$	< 2000 Volts	
Rise Time	< 5 ns	SPE @ gain=10^7
Fall Time	< 10 ns	SPE @ gain=10^7
Linearity ±2%	Up to 40 mA	Peak anode current
Linearity ±5%	< 60 mA	Peak anode current
Dark rate	< 10 KHz	After 15 hours in darkness
Pre-pulse probability	< 0.5%	50 p.e. main pulse
After-pulse probability	< 10%	SPE main pulse

- For AD PMTs, radioactivity should be as low as possible.
- For water Cherenkov detector PMTs, should be able to operate at a pressure up to 2 atmospheres.

Candidate PMTs

- Measurements of single photoelectron spectrum, PMT gain, PMT response time, linearity, pre- and after- pulses and magnetic field effects have been conducted to study 8-inch PMTs from three vendors:
  - Model 9354KB (4 samples) from Electron Tubes.
  - Model R5912 (7 samples) from Hamamatsu Photonics K.K.
  - Model XP1806 (5 samples) from Photonis.

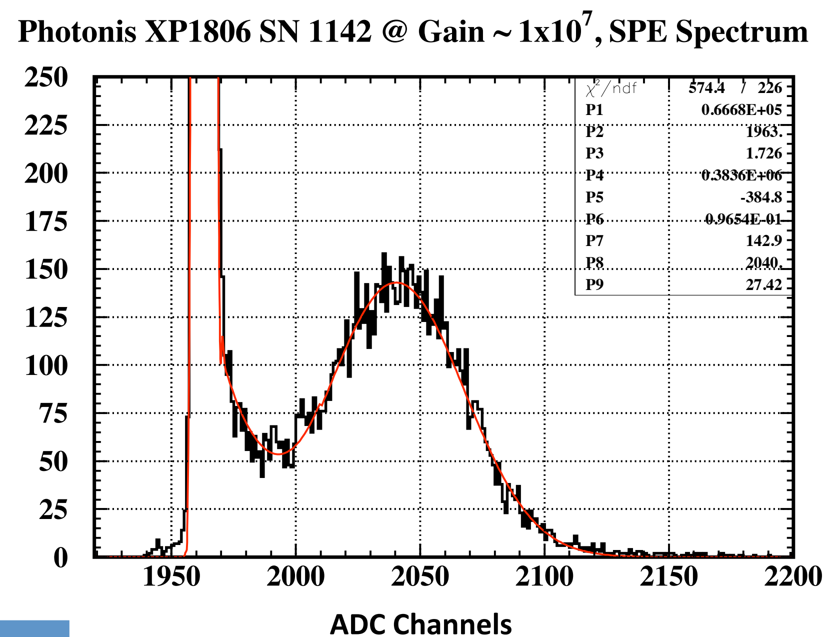
Test Setup



- A test stand is set up at Lawrence Berkeley National Lab to test the candidate PMTs.
- The test stand consists of a dark box with a rotatable PMT holder, blue LED, pulse generator, various NIM & CAMAC modules and DAQ system.
- PMTs are tested with mu-metal shield except the magnetic field effect test.
- Use positive high voltage tapered bases.

Single Photon Electron (SPE) Spectrum

- SPE spectrum is used to determine the PMT absolute gain.
- Figure of merit:
  - Peak to Valley ratio (P/V)
  - Charge resolution.



Typical SPE Distribution

	HV (volt) @ Gain $=10^7$	HV (volt) @ Gain $=3\times10^7$	P/V @ Gain$=10^7$	Charge Resolution @ 10^7
ET 9354KB	1735-1845	1900-2030	2.4-3.2	0.35-0.47
Hamamatsu R5912	1300-1470	1450-1700	2.5-4.3	0.30-0.47
Photonis XP1806	1510-1920	1720-2200	2.5-3.5	0.31-0.43

DYB specification requires:

•P/V to be greater than 2.5.

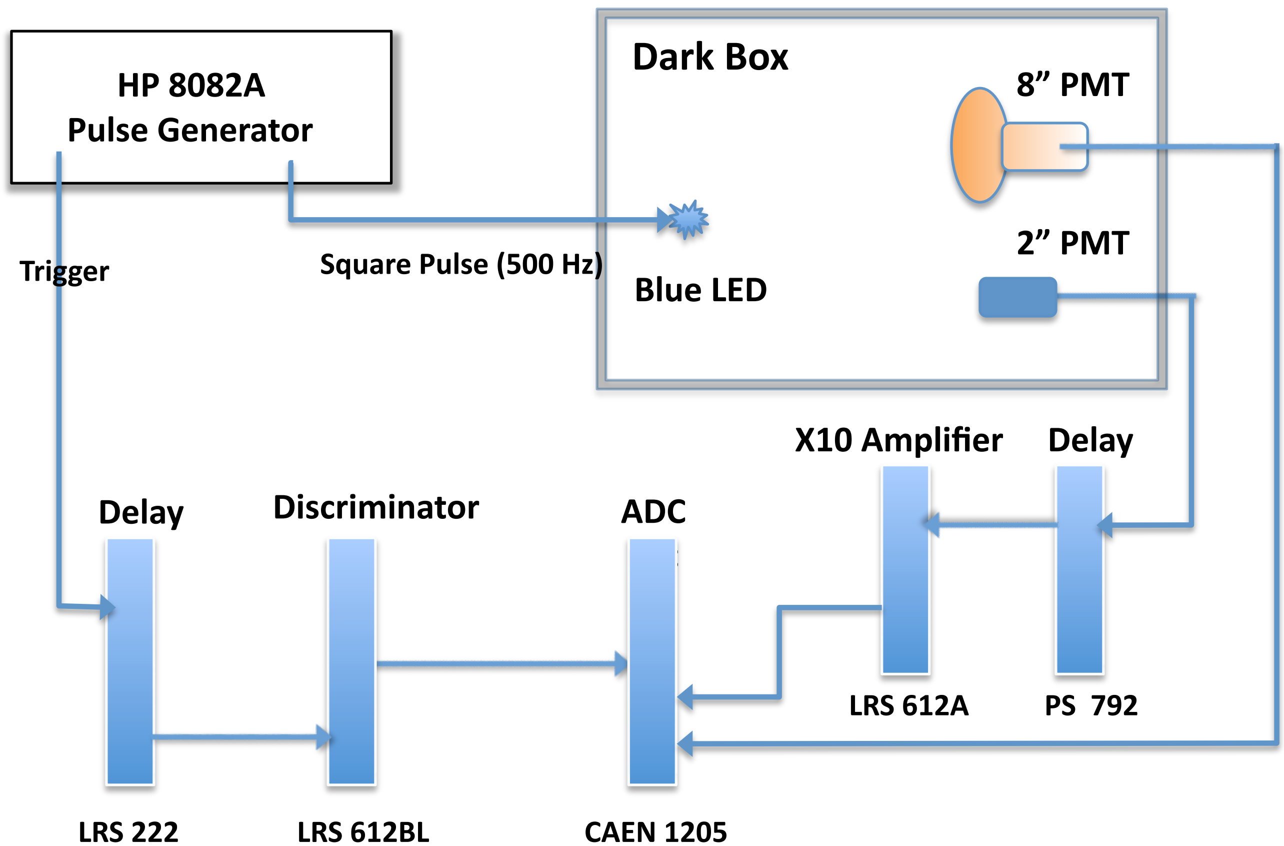
•Can achieve gain=3x10^7 with less than 2000 V.

Rise Time and Fall Time

- Time response of PMTs.
- Fast response is very important for event triggering.
- DYB PMT specification requires
  - For SPE signal at gain=10^7, rise time < 5 ns and fall time < 10 ns.

	Rise Time (ns)	Fall Time (ns)
ET9354KB	3.1 - 3.4	4.1 - 4.4
Hamamatsu R5912	3.1 - 3.2	3.5 - 4.6
Photonis XP1806	~ 4.0	~ 8.0

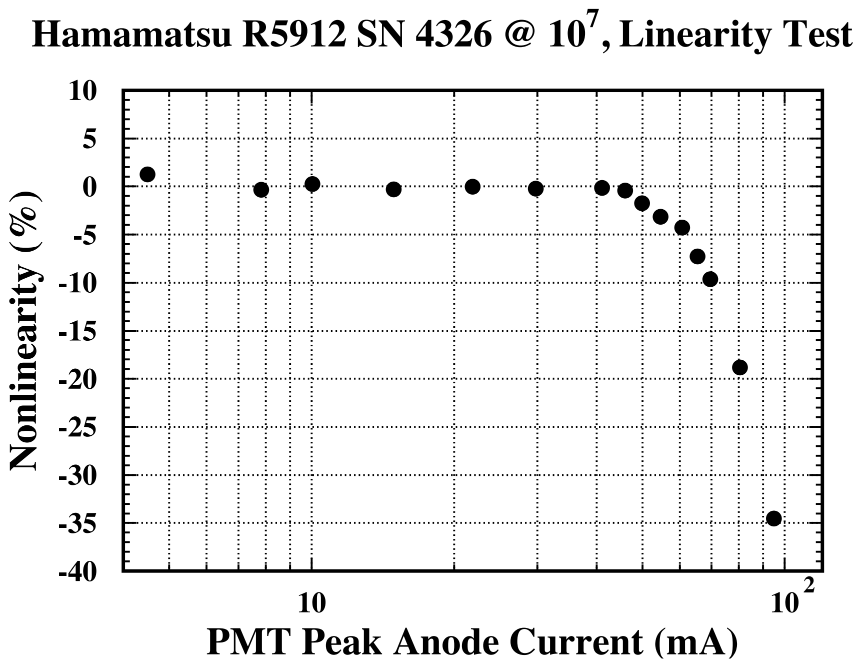
PMT Linearity Measurement



Linearity Measurement Setup

- Use a small 2” PMT as reference PMT. Measure the linearity of the large 8” PMT.
- PMT amplitude is measured by a scope.
- PMT charge is measured by ADC.

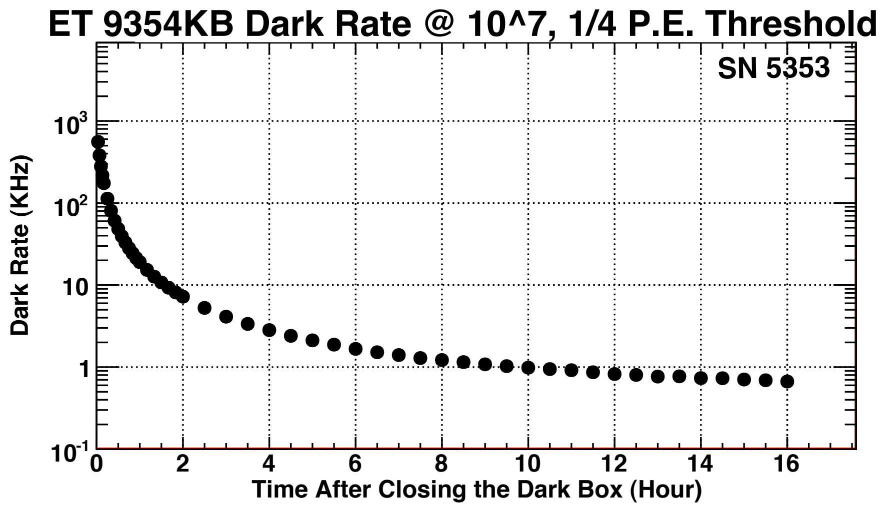
PMT Linearity Measurement



	2% @ Peak Anode Current (mA)	5% @ Peak Anode Current (mA)
ET9354KB	80-105	95-125
Hamamatsu R5912	45-52	50-62
Photonis XP1806	45-85	50-105

- DYB PMT linearity requirement:
  - Linearity is within ±2% for peak anode current from 0 to 40 mA.
  - Nonlinearity is less than 5% for peak anode current up to 60 mA.

PMT Dark Rate



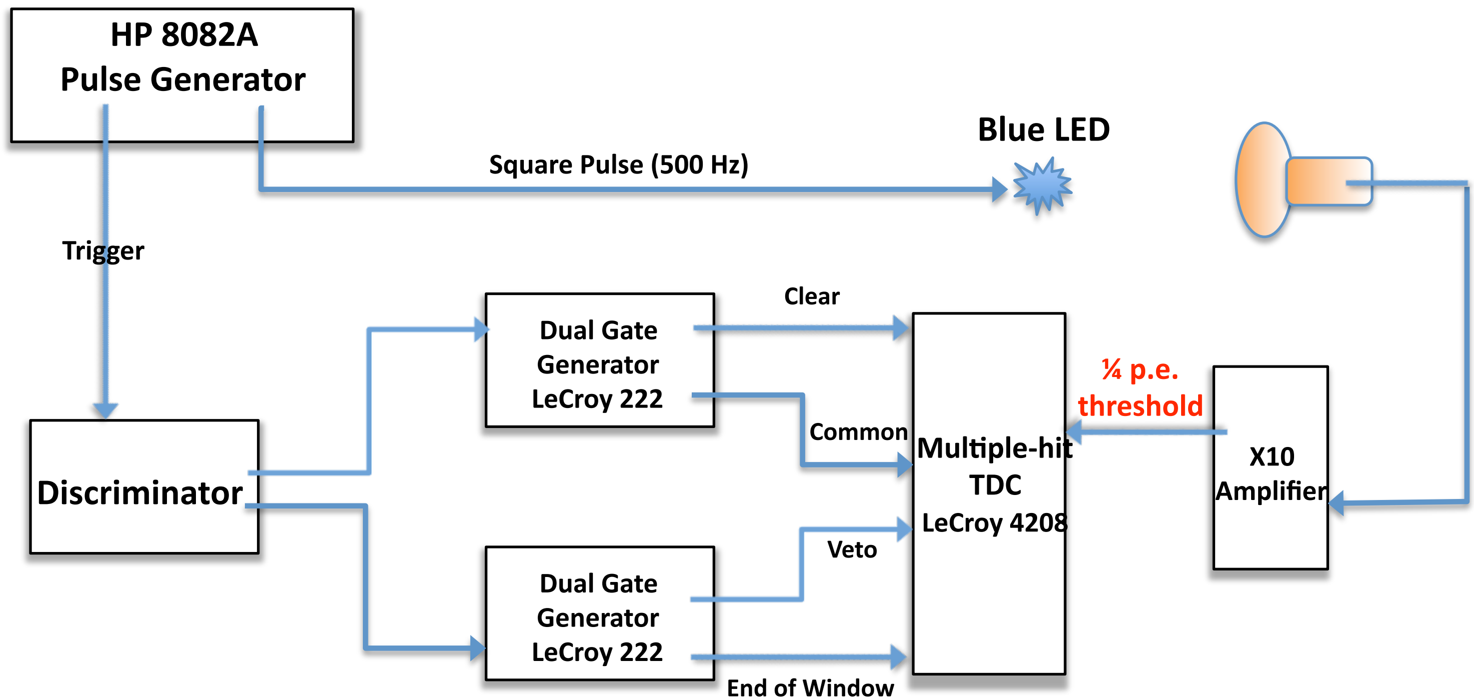
Typical dark rate distribution as function of time in darkness

- PMT dark rate is measured by a scaler with a ¼ p.e. threshold as function of time of PMT in darkness.
- DYB specification requires that the dark rate will be less than 10 KHz after 15 hours in darkness.

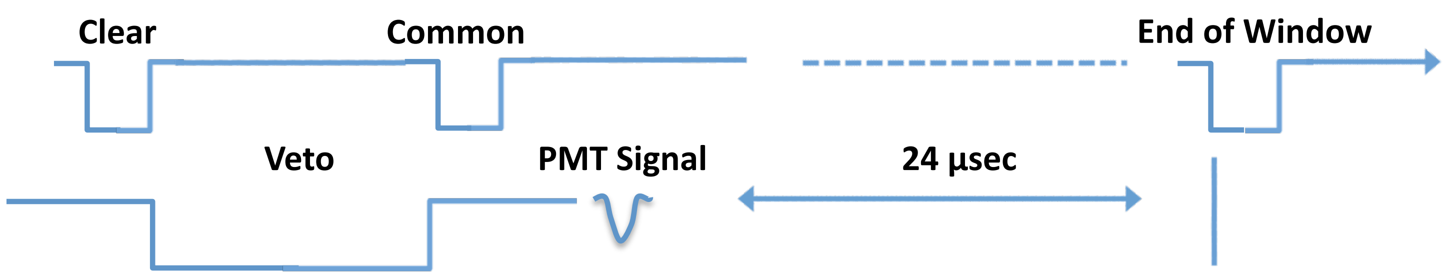
	ET9354KB	Hamamatsu R5912	Photonis XP1806
Dark Rate After 15 Hours	~1 KHz	~1-2 KHz	~1-6 KHz

Pre- & After-Pulse Measurement

Setup

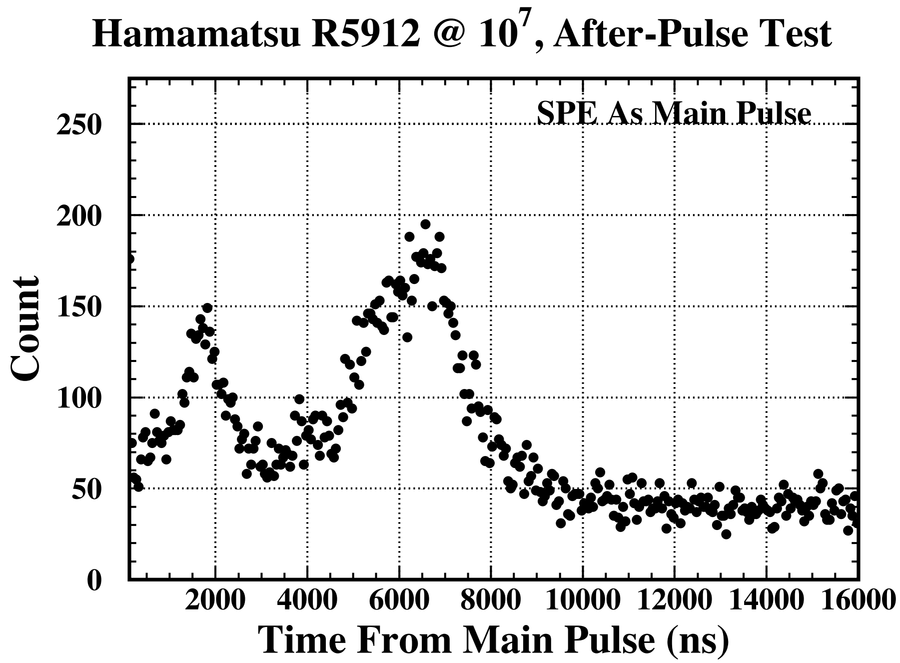


Timing Diagram



Pre- & After- Pulse Measurements

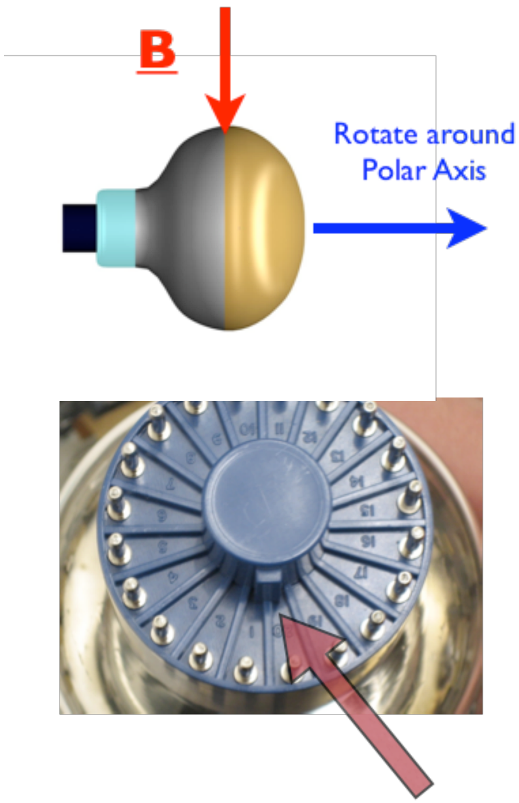
	Pre-pulse Probability (%)	After-pulse Probability (%)
ET9354KB	0.2 - 0.4	2.1 - 3.2
Hamamatsu R5912	0.1 - 0.5	2.2 - 2.5
Photonis XP1806	0.1 – 0.3	0.9 – 3.9



Typical after-pulse distribution

Specification: Pre-pulse probability is less than 0.5% (50 p.e. main pulse) and after-pulse probability is less than 10% and typically 2% (SPE as main pulse).

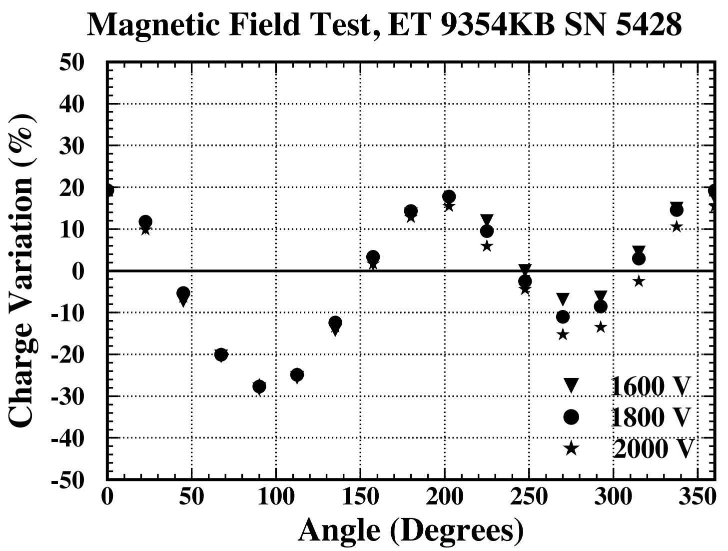
Magnetic Field Effect

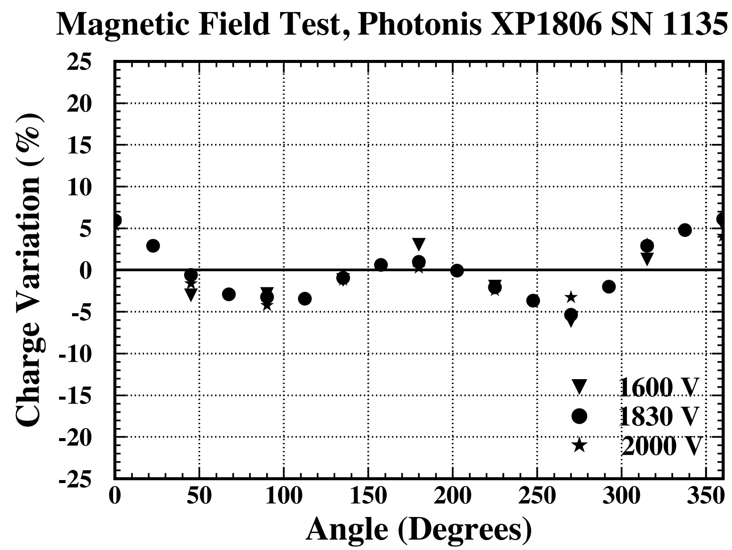


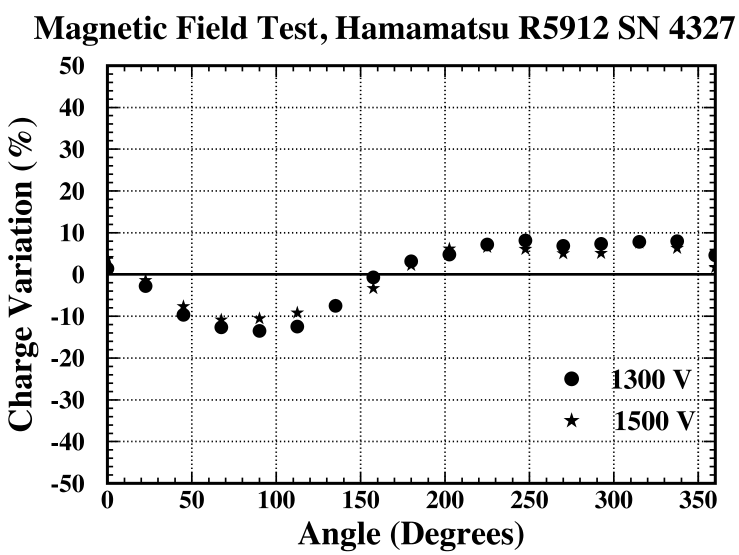
Key on the PMT between pin 1 and 20 is used as Reference Direction

- Local magnetic field is about 0.5 gauss.
- Shine light evenly onto the PMT.
- Magnetic field perpendicular to the polar axis of the PMT.
- Rotate the PMT around its polar axis while keep the light unchanged
- Measure the output charge of PMT as function of angle between local magnetic field and reference direction on the PMT.

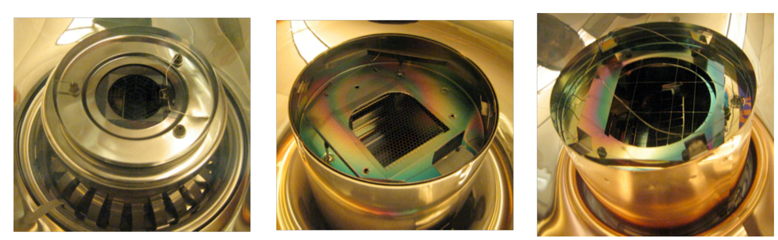
Magnetic Field Effect







- Charge variation due to magnetic field varies among PMTs from different vendors.
- Magnetic field affects PMT's collection efficiency.
- The larger the first dynode, the less being affected by the magnetic field.



From left to right: ET, Hamamatsu and Photonis tubes

PMT Radioactivity

Radioactivity of PMT glass

	^{238}U (Bq/Kg)	^{232}Th (Bq/Kg)	^{40}K (Bq/Kg)
ET9354KB	1.0	0.3	4.0
Hamamatsu R5912 [1]	1.9	1.3	5.1
Hamamatsu R5912 [2]	0.9	0.2	0.6
Photonis XP1806	2.8	0.3	5.3

1. Low background glass.
2. Ultra low background glass.

- PMT bulb should be made of low background glass.
- Materials used to make the PMT dynodes and other components should contain very little radioactive materials.

PMT Assembly Pressure Test

- PMT assemblies with sealed base from Hamamatsu and Photonis have been pressure tested.
- These PMTs are subjected to 2 atmospheres in a water tank at Rensselaer Polytechnic Institute:
  - Hamamatsu PMT assemblies has been running with no problem for several weeks.

Conclusion

- We have evaluated the 8" candidate PMTs from Electron Tubes, Hamamatsu and Photonis.
- All PMTs have good SPE spectra, good linearity, low dark rates as well as low pre- and after- pulsing.