Vacuum based Photon Detectors

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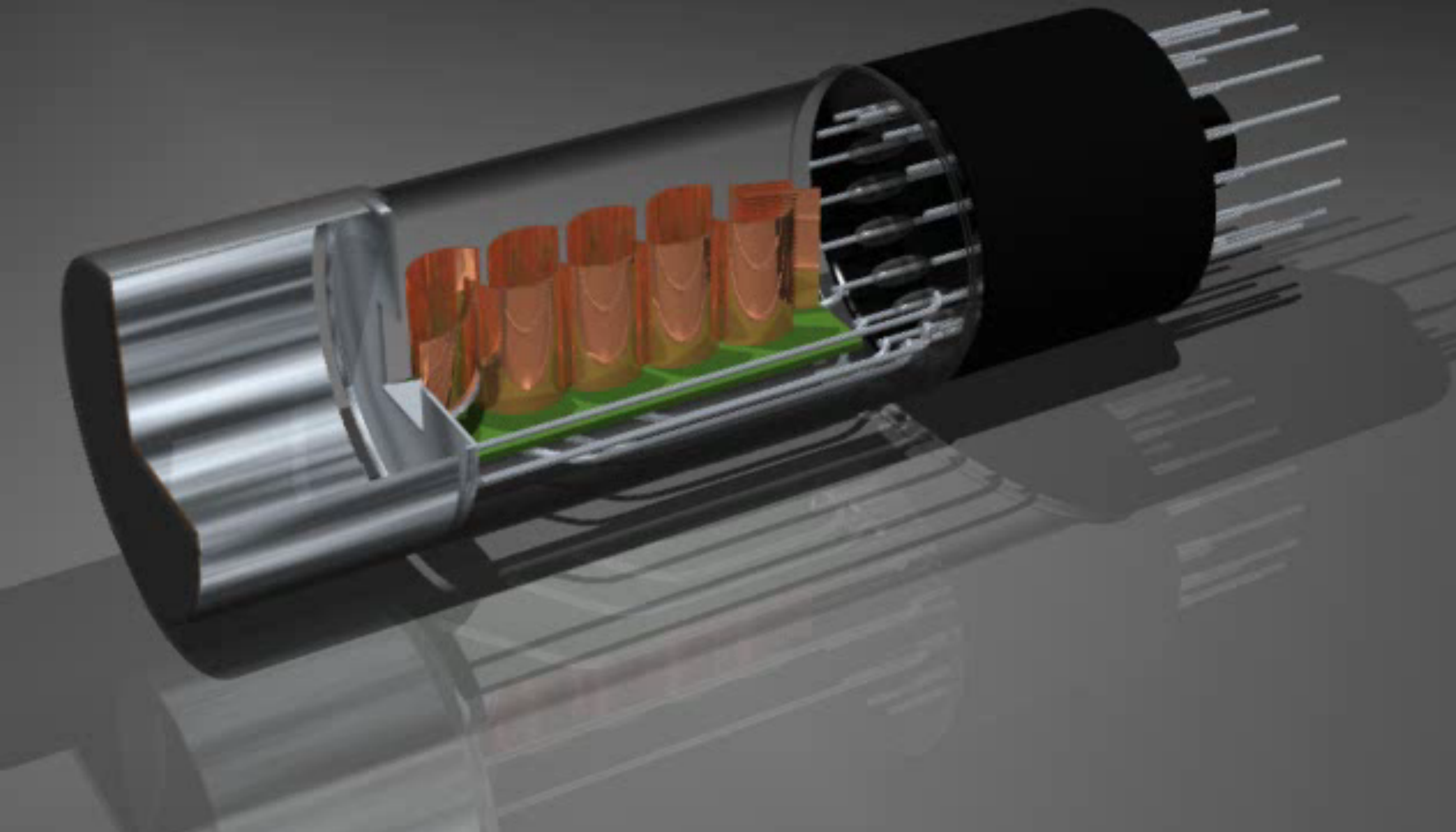
Outline

- Concept of Photomultiplier
- Basic Properties
  - QE, Gain, Time Response
- Imperfect Behavior of PMT
  - Linearity, Uniformity, Noise…
- Other Vacuum Devices
  - Hybrid PD/APD
  - Applications
- Energy Resolution
- Summary

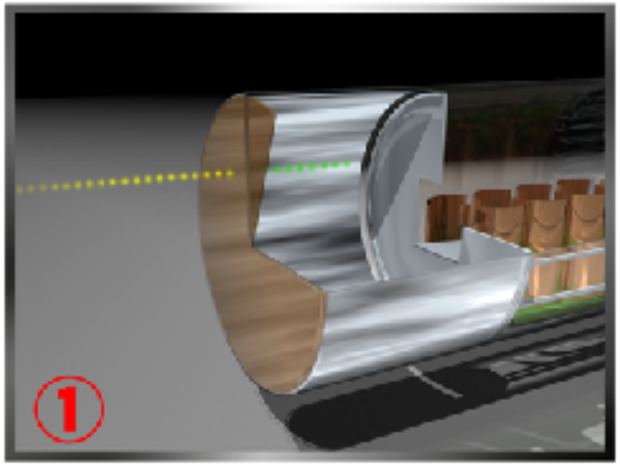
Concept of PMT

PMT (Photomultiplier Tube)

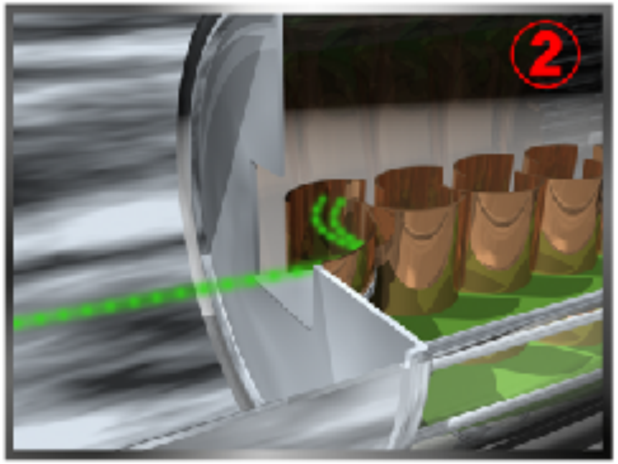

Super-Kamiokande
11,200 of 20" PMTs



Operation of Head-On Type PMT



signal light->photoelectron



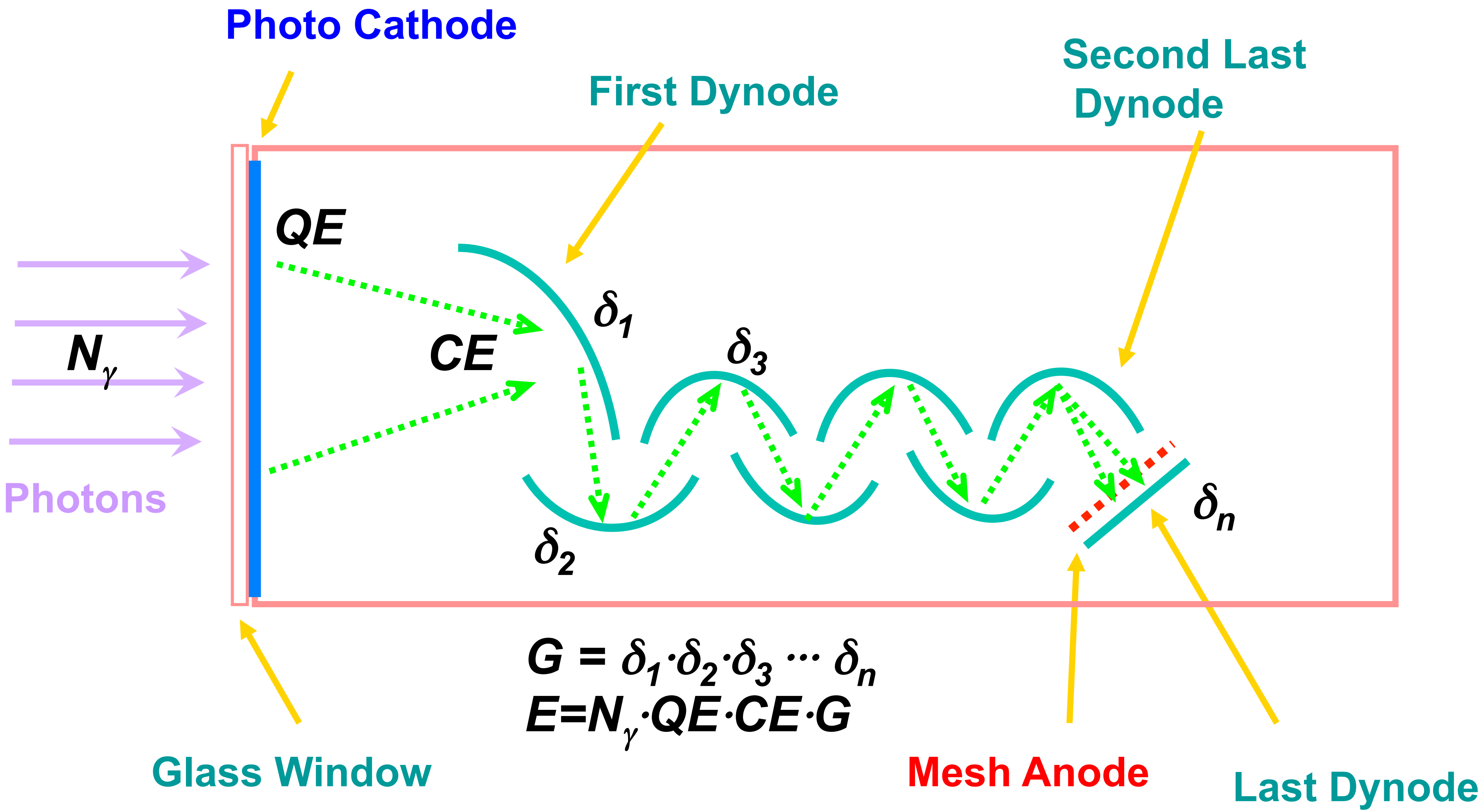
photoelectron->Dy1

electron-> multiplication

cascade multiplication

electric signal from anode

Structure of Linear-focus PMT

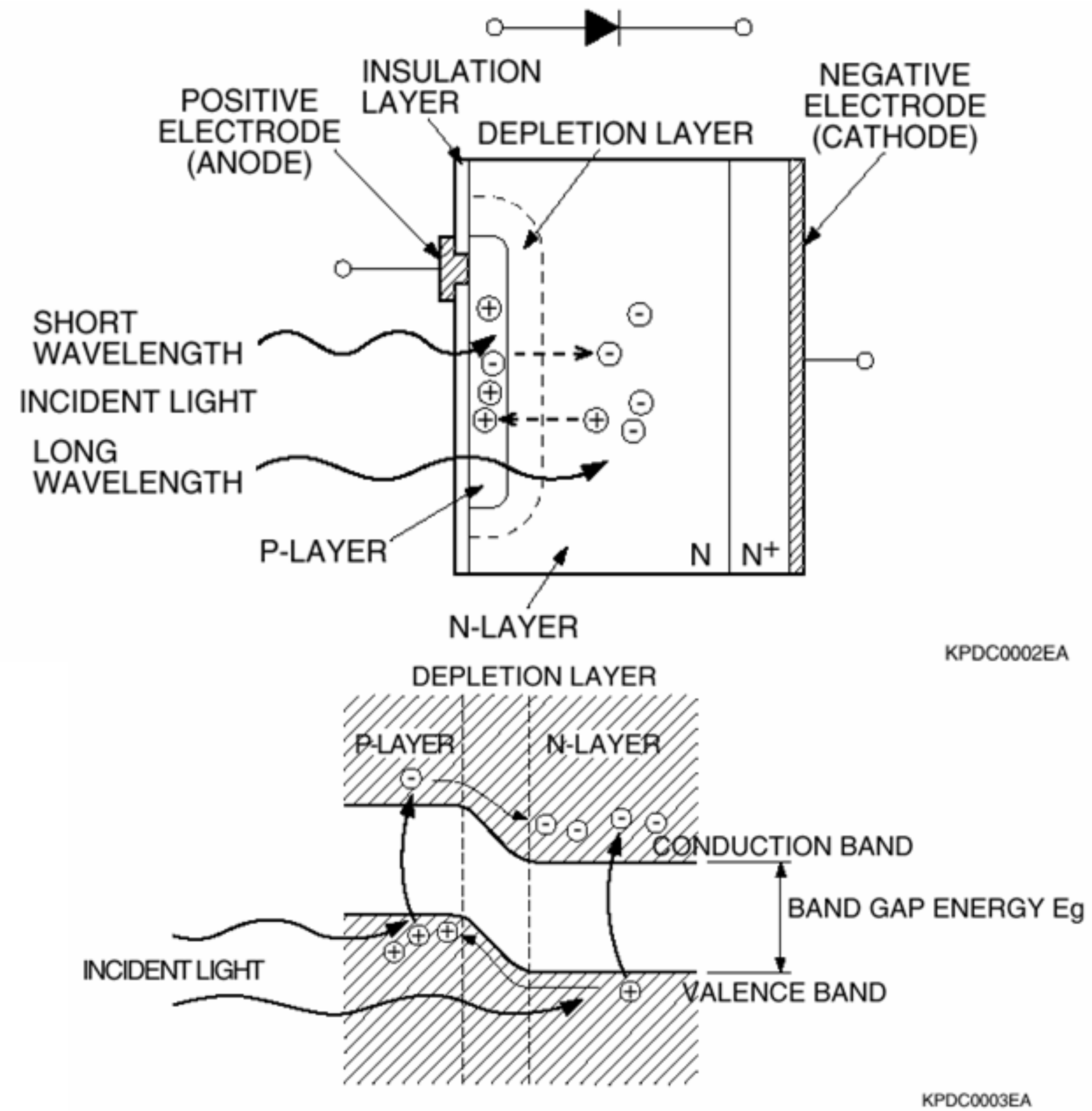


$$G = \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$$

$$E = N_\gamma \cdot QE \cdot CE \cdot G$$

Principle of Silicon Photodiode

- Gain = 1.0
- QE ~ 100%
- Extremely Stable
- Large Dynamic Range



FAQ

- **Why still PMT? Why not Silicon Photodiode?**
  - Intrinsically high gain
  - Low noise – photon counting
  - Fast speed
  - Large area

    but

  - Poor Quantum Efficiency
  - Bulky
  - Expensive

Purpose of Photon Detector

- **Observe all the quantities of photons as accurate as possible.**
  - The number of photons: E
  - Arrival time of photons: T
  - Position of photons: X, Y, Z

- **Primary purpose of vacuum detectors:**
  - Very small number of photons: < 100 photons
  - Accurate time of photons: < 10 nsec

Basic Properties

Outline

- **Fundamental Parameters of PMT**
  - Quantum Efficiency (QE)
  - Photoelectron Collection Efficiency (CE)
  - Gain (G)
  - Excess Noise Factor (ENF)
- **How to Measure These Parameters**

⇩

- **Energy Resolution (σ/E)**

Quantum Efficiency (QE)

Quantum Efficiency (QE)

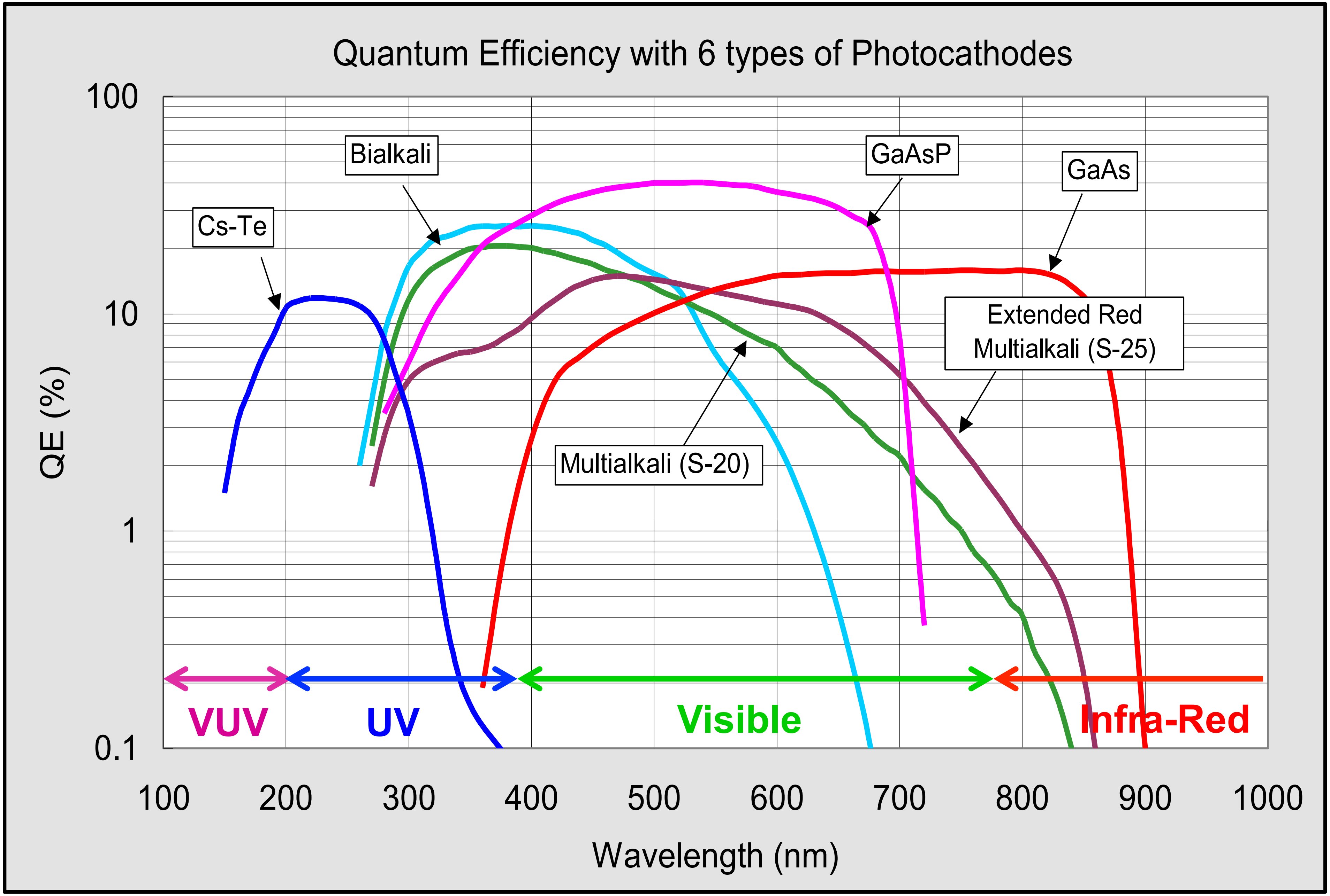
- **Definition:**

$$QE \equiv \frac{(\#Emitted\_Photoelectrons)}{(\#Insident\_Photons)}$$

$$= \frac{N_{pe}}{N_{\gamma}}$$

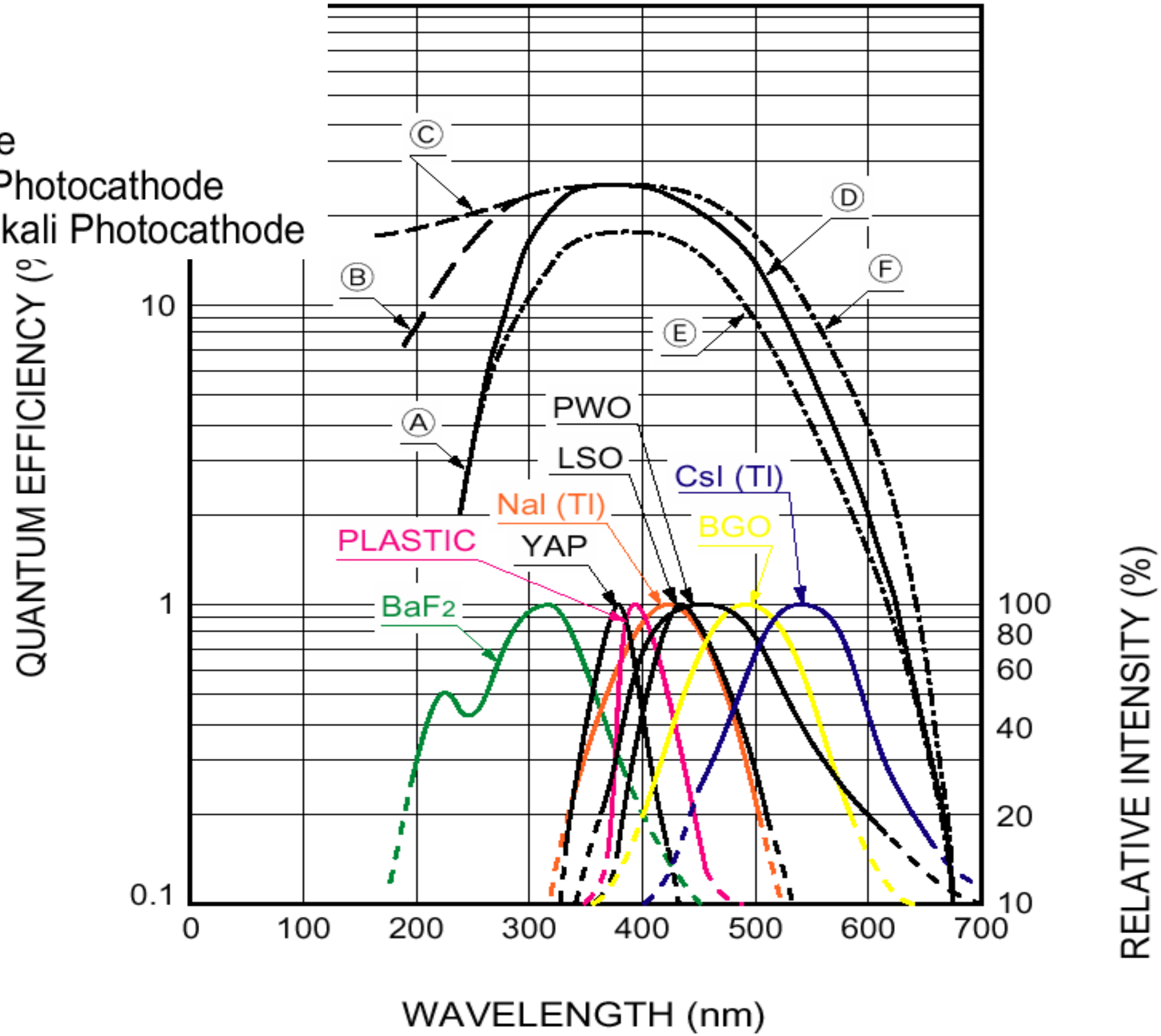
- **The single most important quantity**

QE curves of 6 types



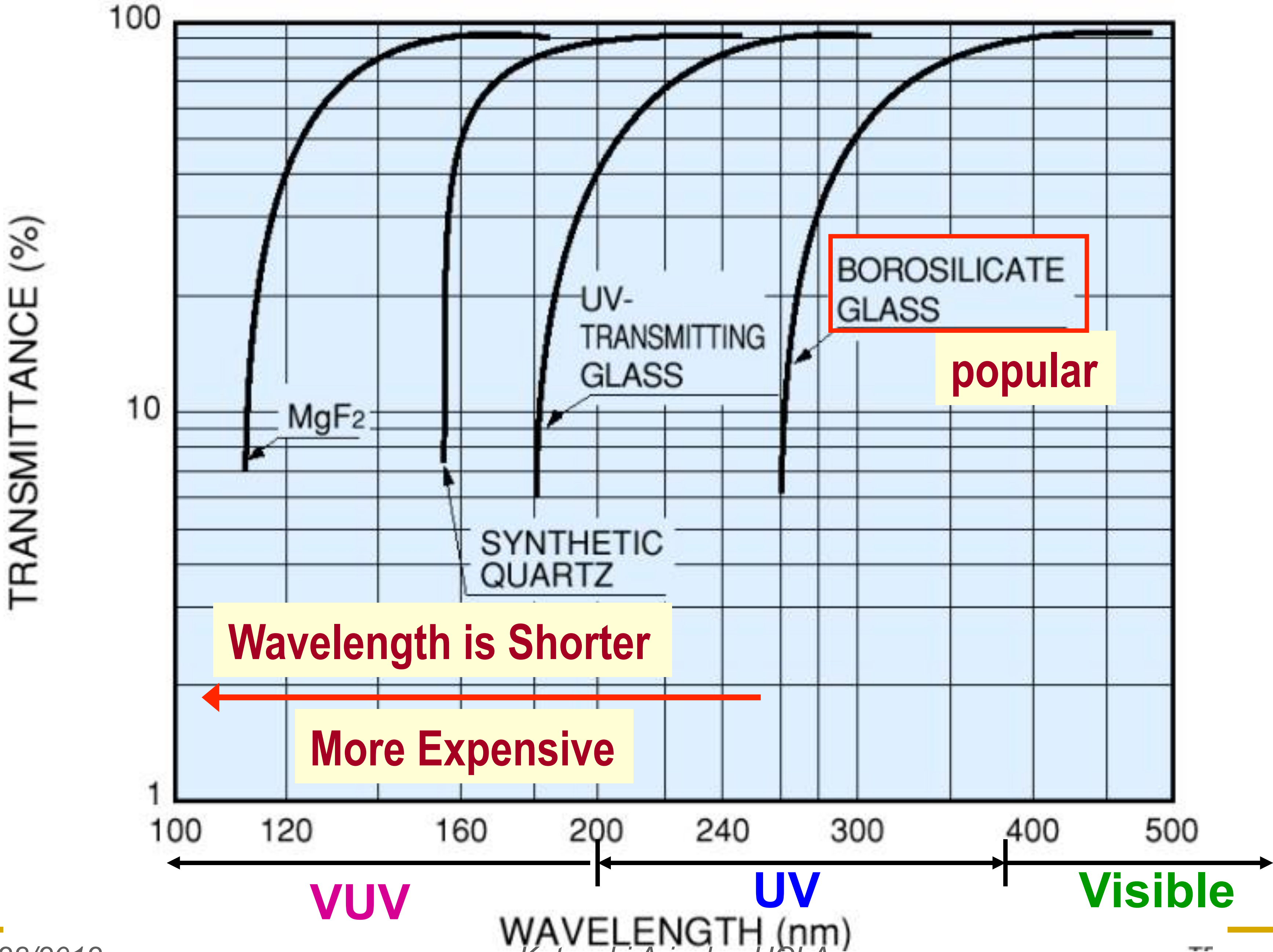
Typical QE

Ⓐ: Borosilicate Glass
Ⓑ: UV Glass
Ⓒ: Synthetic Silica
Ⓓ: Bialkali Photocathode
Ⓔ: High Temp. Bialkali Photocathode
Ⓕ: Extended Green Bialkali Photocathode



Bialkali:
Sb-Rb-Cs
Sb-K-Cs

Transmittance of windows



FAQ

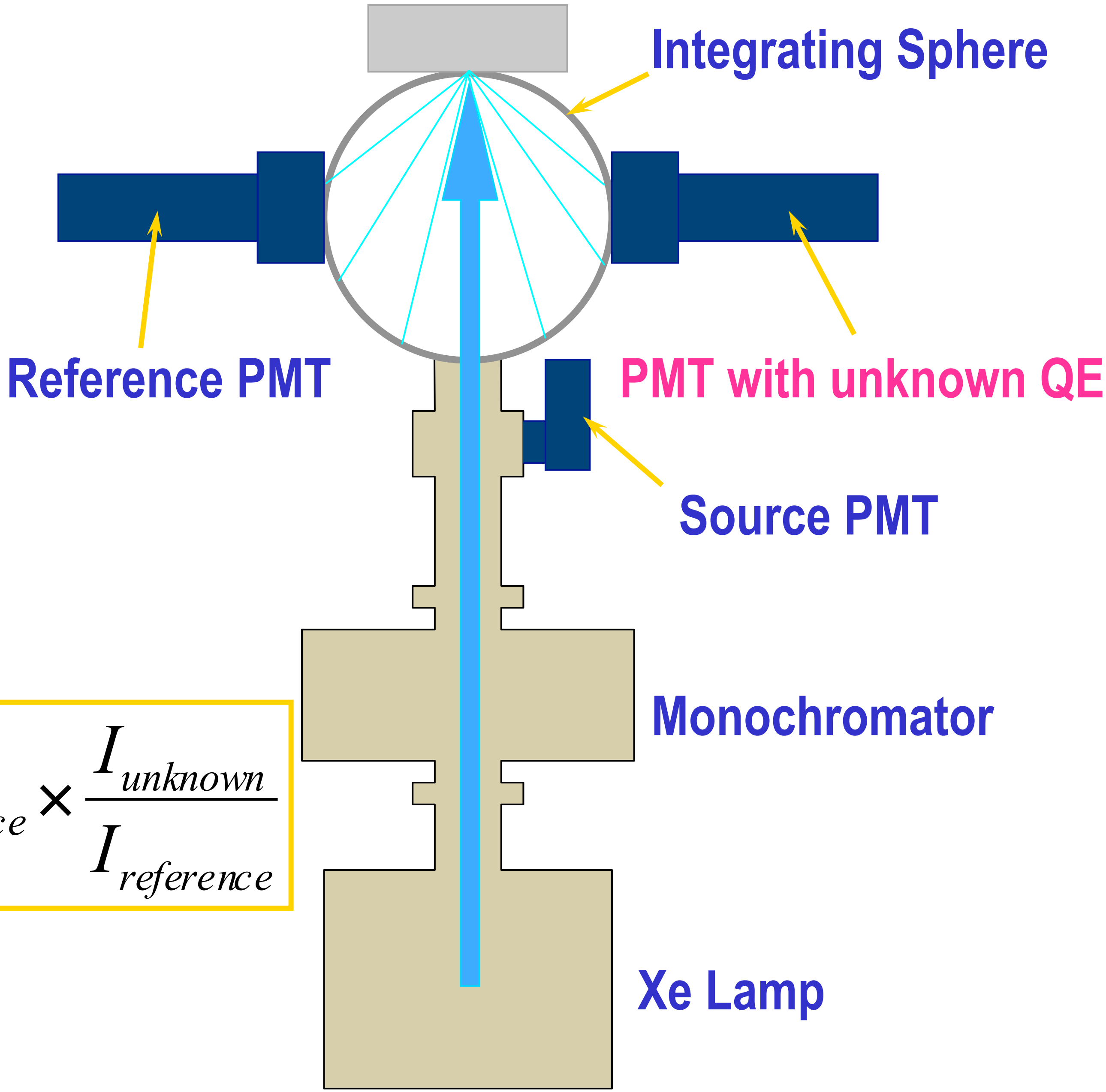
- **Why is QE limited to ~40% at best?**
  - **Competing two factors:**
    - **Absorption of photon**
    - **Emission of photo-electrons**
  - **Isotropic emission of photo-electrons.**

FAQ

➢ How can we measure QE?

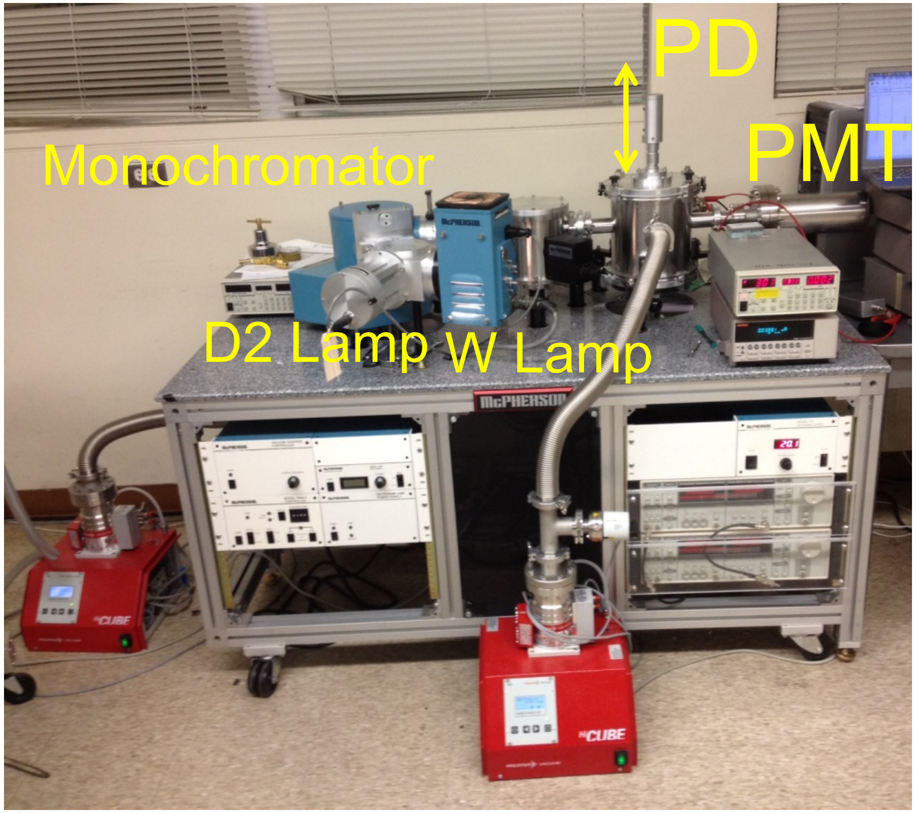
- Connect all the dynodes and the anode.
- Supply more than +100V for 100% collection efficiency.
- Measure the cathode current (I_C).
- Compare I_C with that of a reference photon-detector with known QE.

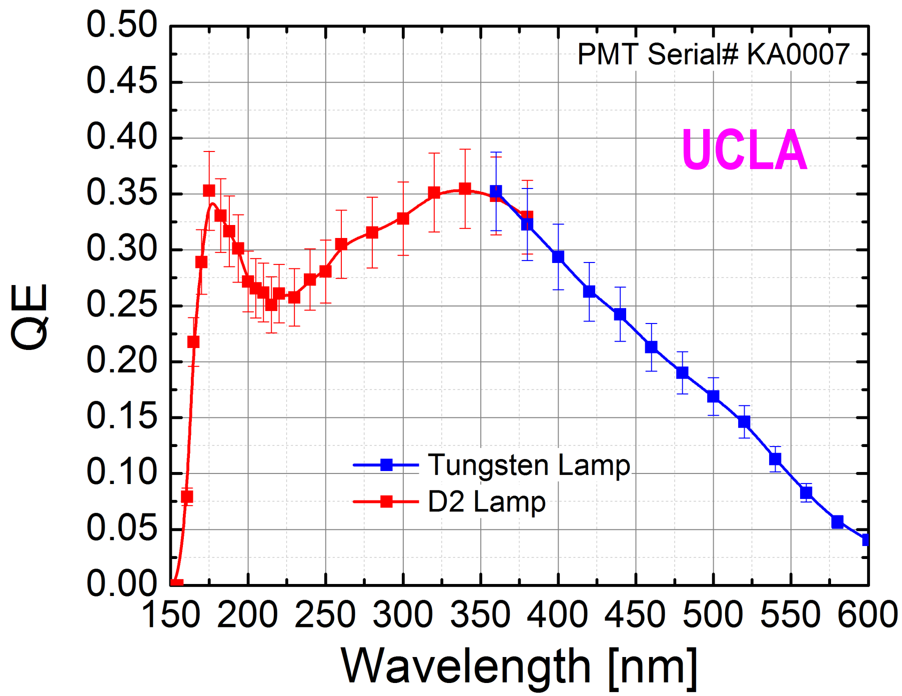
UCLA QE System

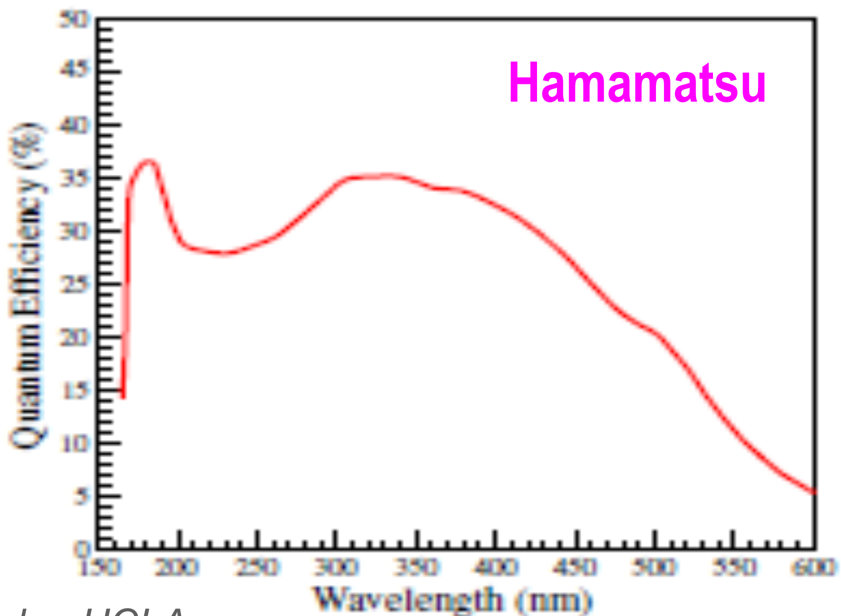


$$QE_{unknown} = QE_{reference} \times \frac{I_{unknown}}{I_{reference}}$$

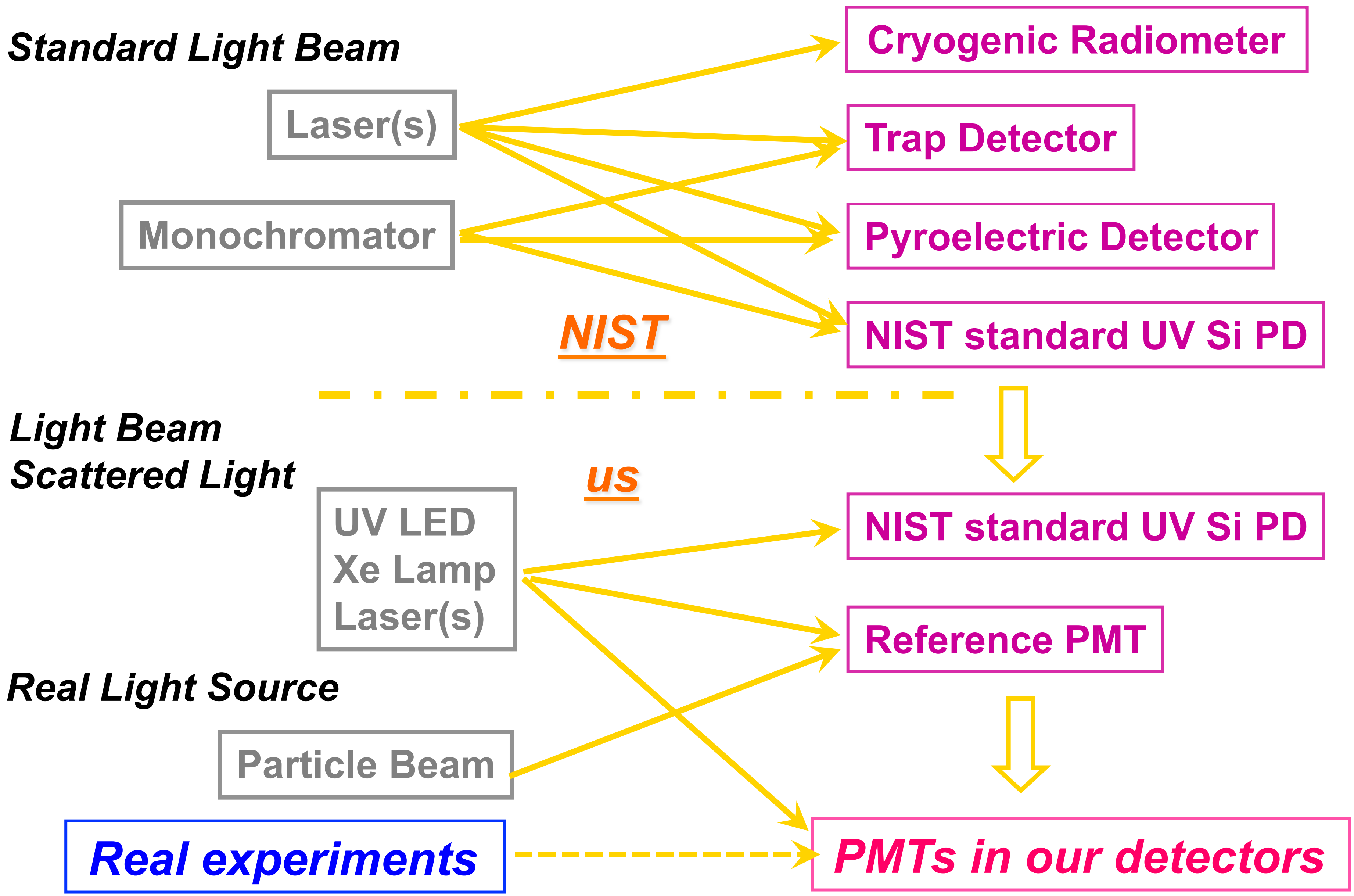
UCLA Vacuum UV QE System





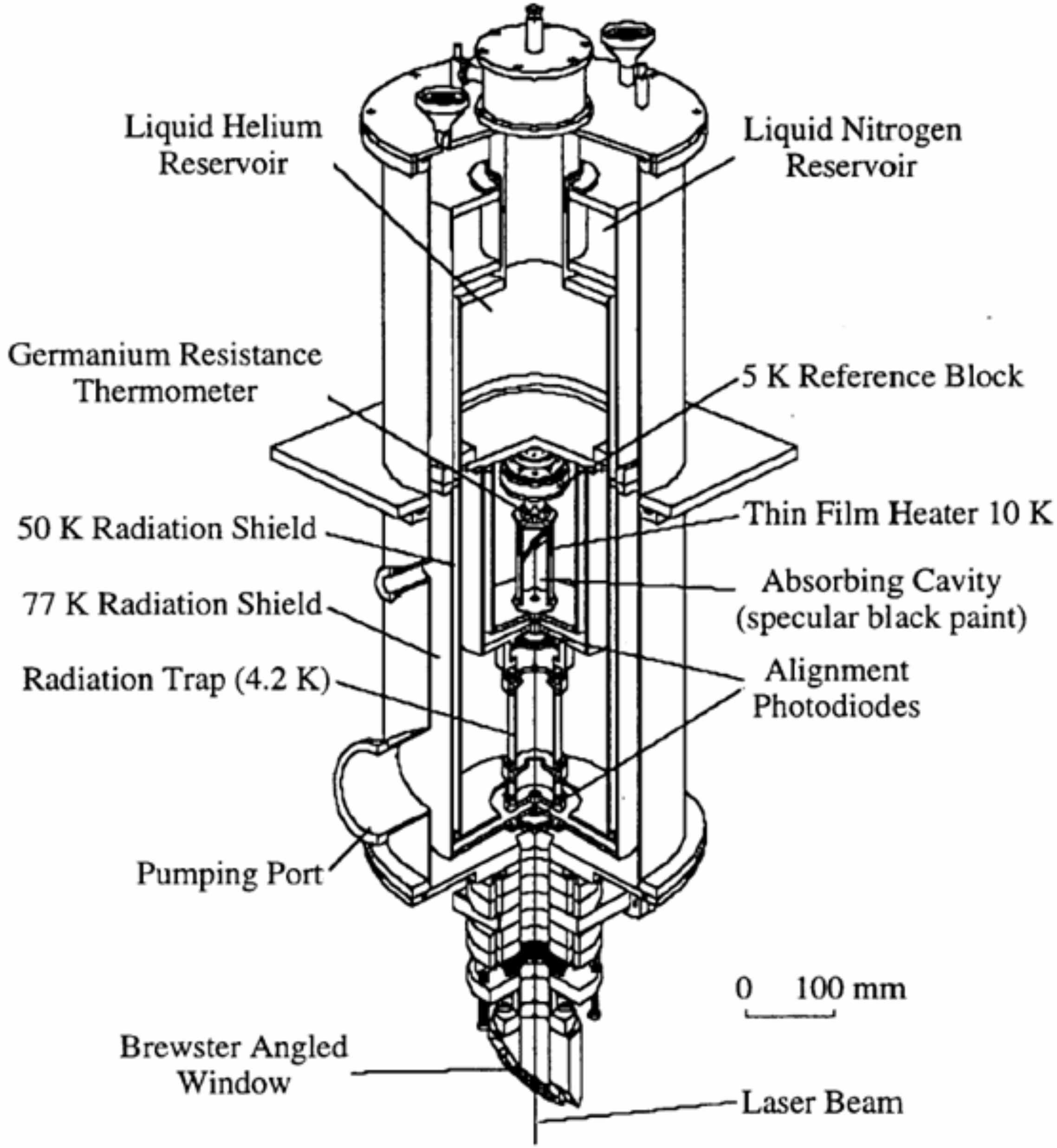


Propagation Chain of Absolute Calibration of Photon Detectors

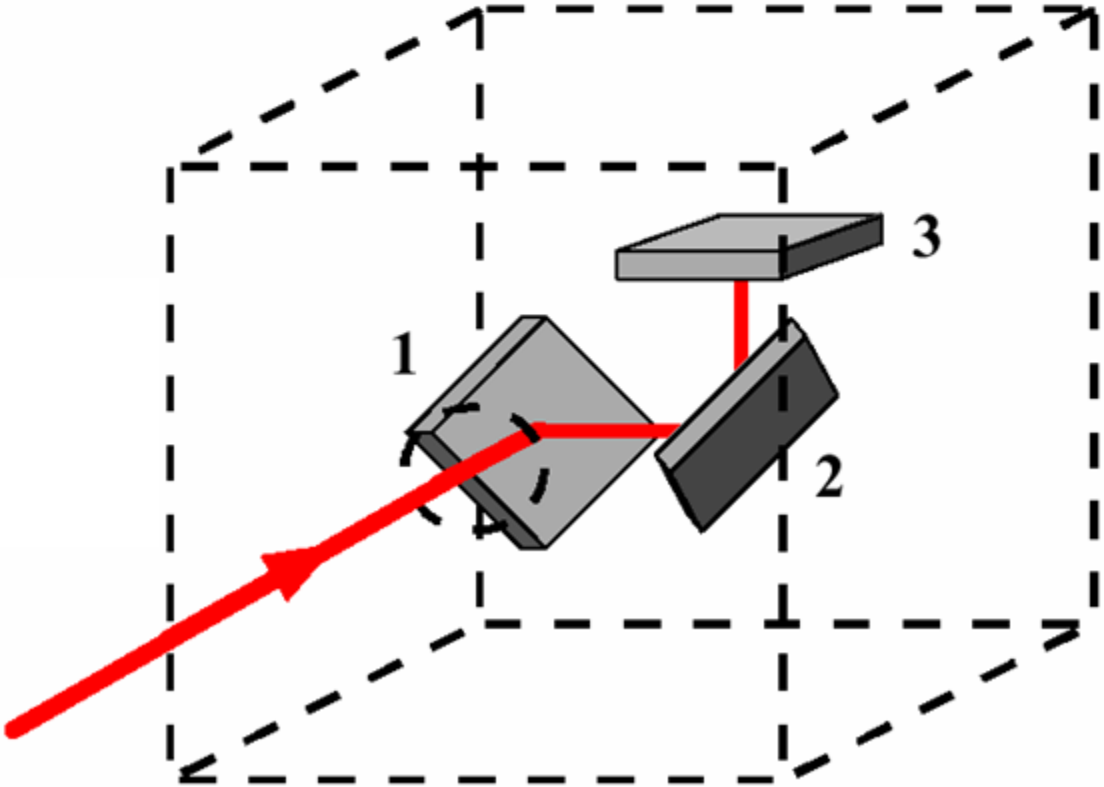


NIST High Accuracy Cryogenic Radiometer (HACR)

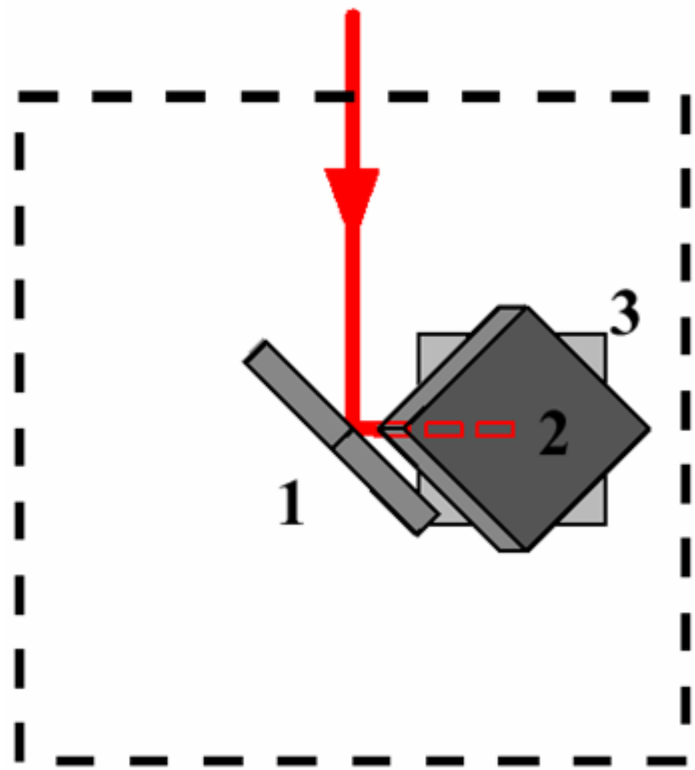
- Photon energy is converted to heat.
- Heat is compared with resistive (Ohmic) heating.
- 0.021% accuracy at 1mW.
- This is the origin of absolute photon intensity.



Trap Detector

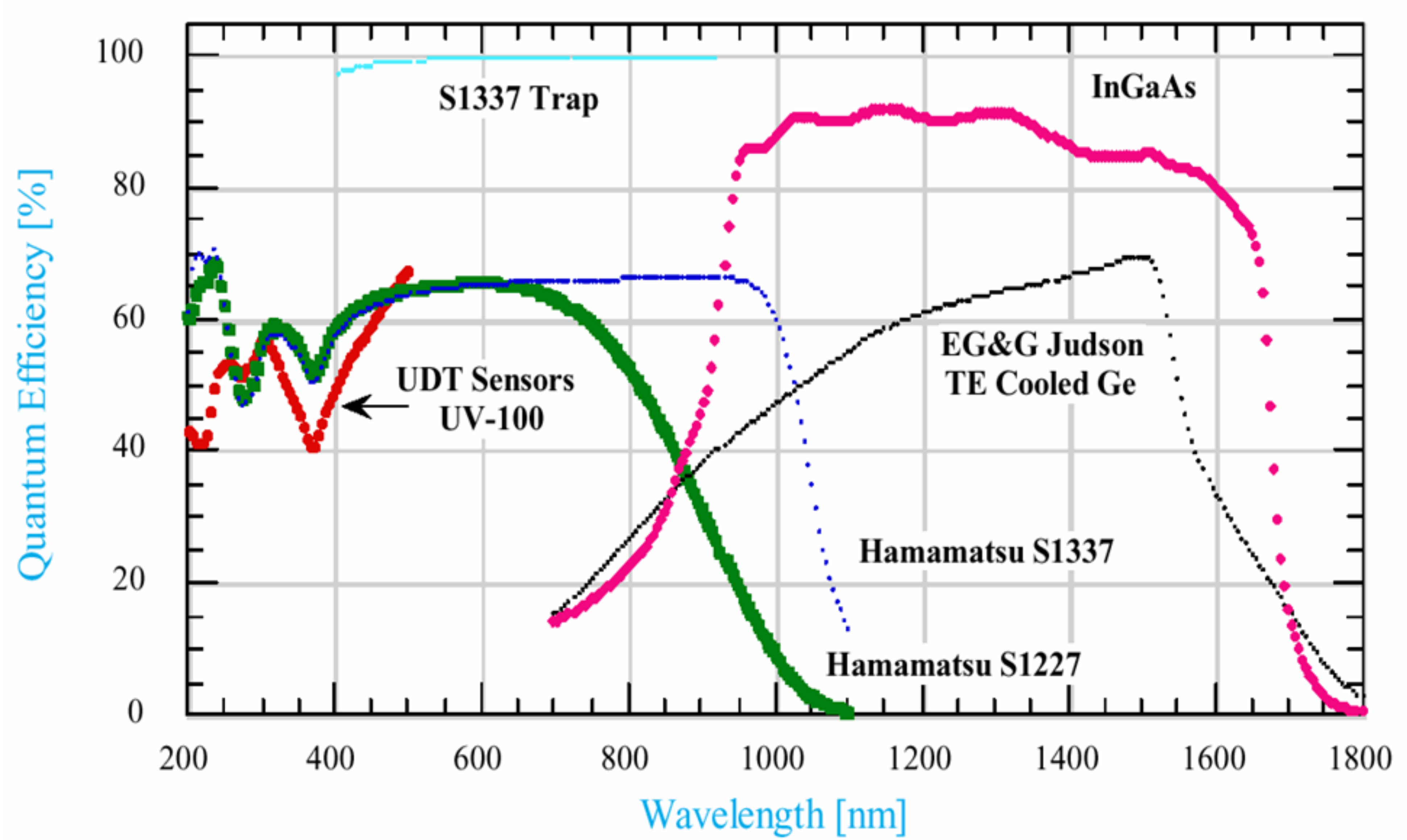


Front View

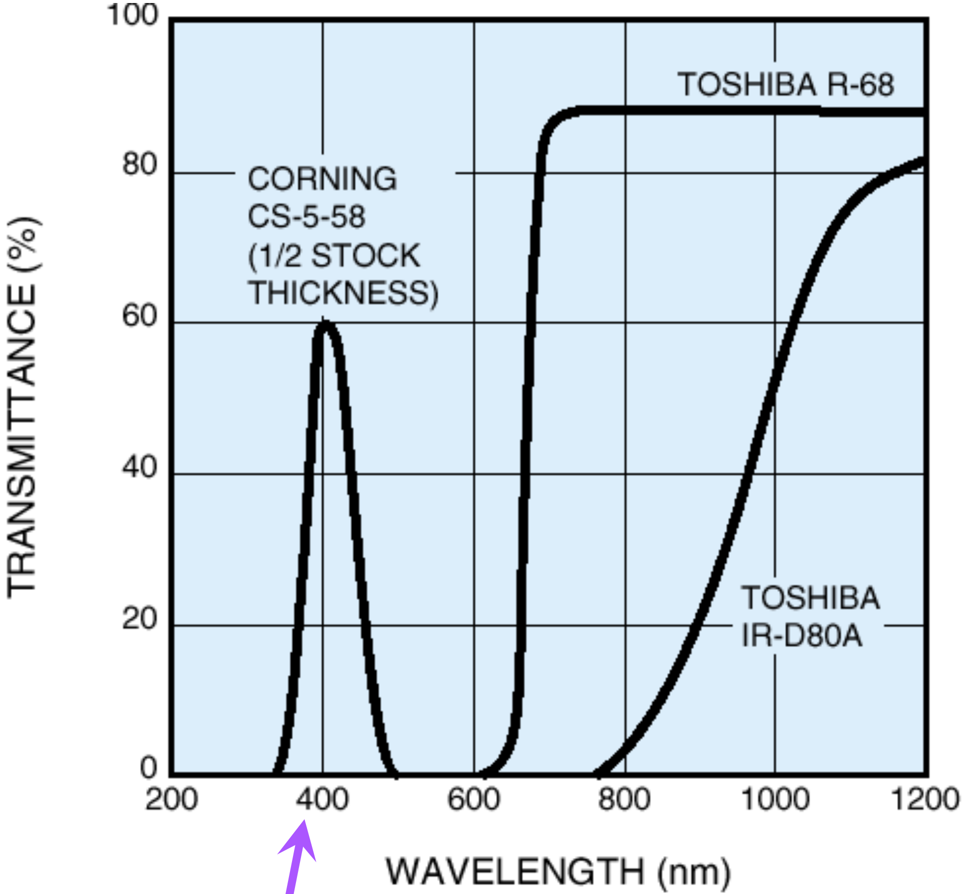


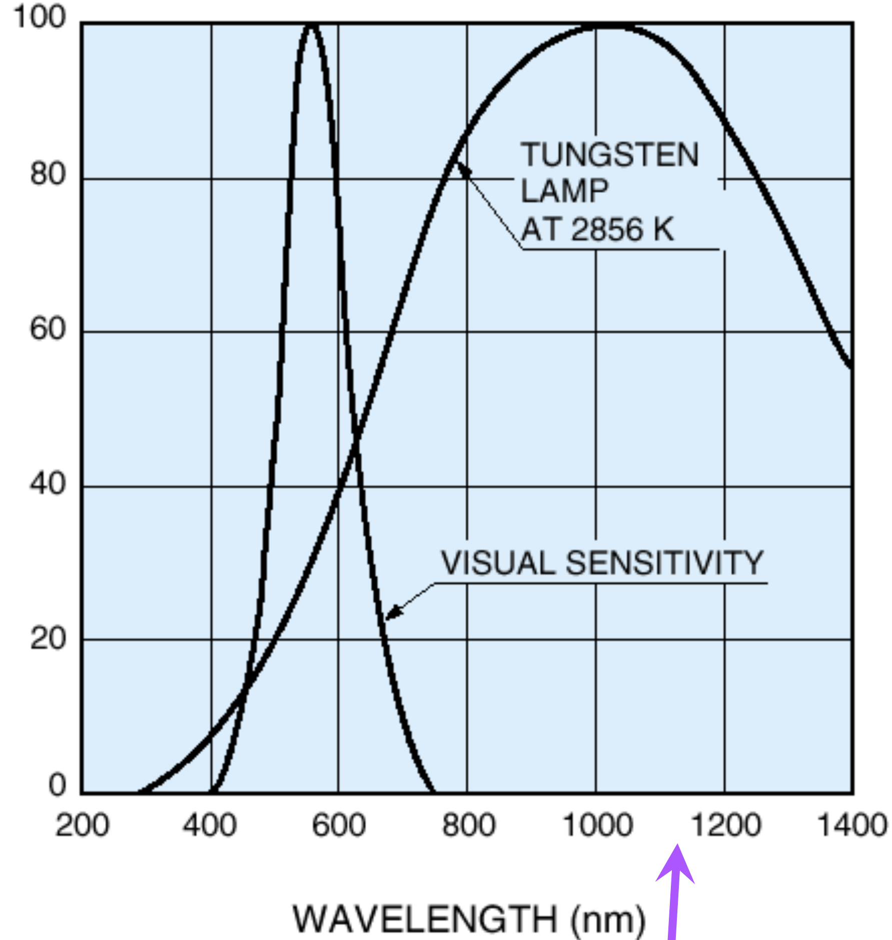
Bottom View

NIST Standards: Quantum efficiencies of typical Si, InGaAs, and Ge photodiodes



S_k (Cathode Sensitivity) and S_{kb} (Cathode Blue Sensitivity)





Filter for S_{kb}

Lump for S_k

Collection Efficiency (CE)

- **Definition**

$$CE \equiv \frac{(\#PE\_captured\_by\_1st\_Dynode)}{(\#Emitted\_Photoelectrons)}$$

FAQ

- **How can we measure Collection Efficiency?**
  - Measure the Cathode current (I_C).
  - Add 10^{-5} ND filter in front of PMT.
  - Measure the counting rate of the single PE (S).
  - Take the ratio of $S \times 1.6 \times 10^{-19} \times 10^{5} / I_C$.

Detective Quantum Efficiency (DQE)

➢ Definition:

$$DQE \equiv \frac{(\#PE\_captured\_by\_1st\_Dynode)}{(\#Insident\_Photons)}$$

$$= QE \cdot CE$$

- ***Often confused as QE by "Physicists"***

FAQ

➢How can we measure Detective QE?

- Use a weak pulsed light source (so that >90% pulse gives the pedestal.)
- Measure the counting rate of the single PE (S).
- Compare S with that of PMT with known DQE.

Dynode Structure

PMT Types

< SIDE-ON TYPE >

< SIZE >

1/2 inch & 1-1/8 inch

< Features >

Compact

Relatively Cheap

< HEAD-ON TYPE >

< SIZE >

3/8 inch ~ 20 inch

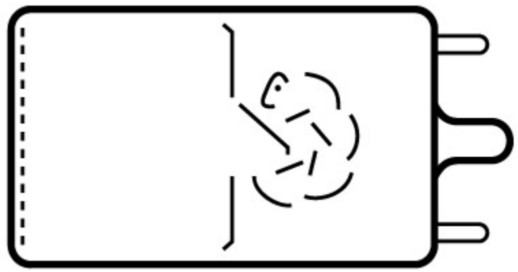
< Features >

Variety of sizes, Direct coupling

Dynode Structures – Side-on vs. Head-on

CIRCULAR CAGE

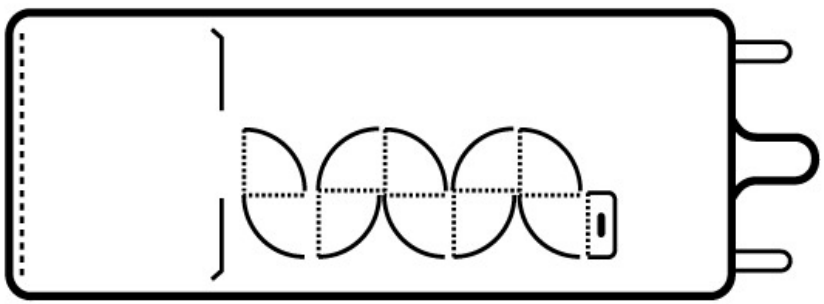
< SIDE-ON >



< HEAD-ON >

- Compact
- Fast time response (mainly for Side-On PMT)

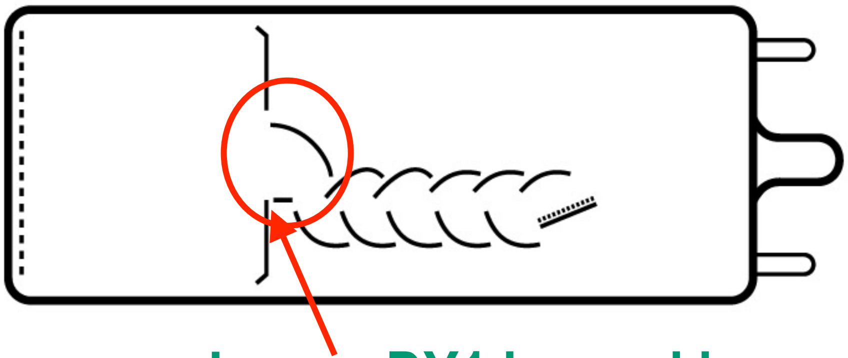
BOX & GRID



- Good CE (Good uniformity)
- Slow time response

Dynode Structures – Linear Focus vs. Venetian Blind

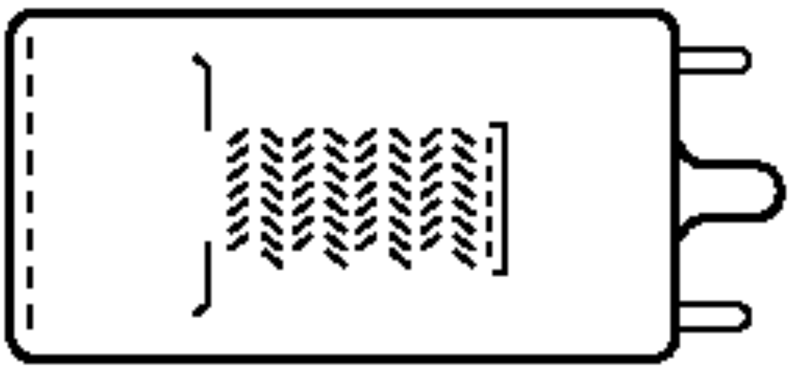
LINEAR FOCUSED (CC+BOX)



Fast time response
Good pulse linearity

Larger DY1 is used in recent new PMTs (Box & Line)

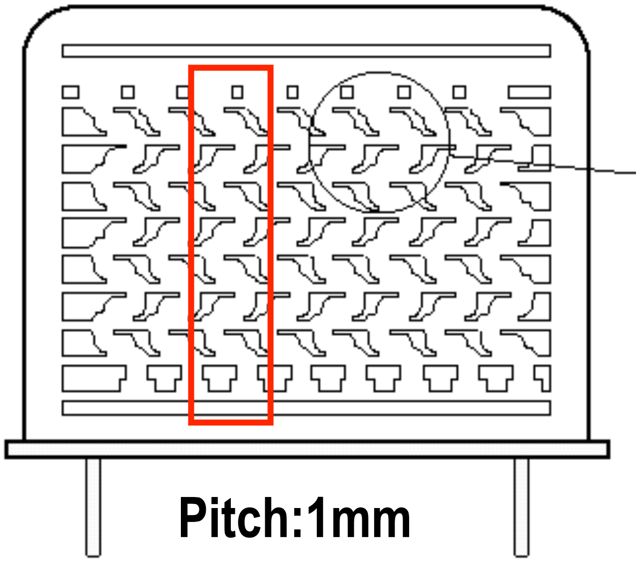
VENETIAN BLIND



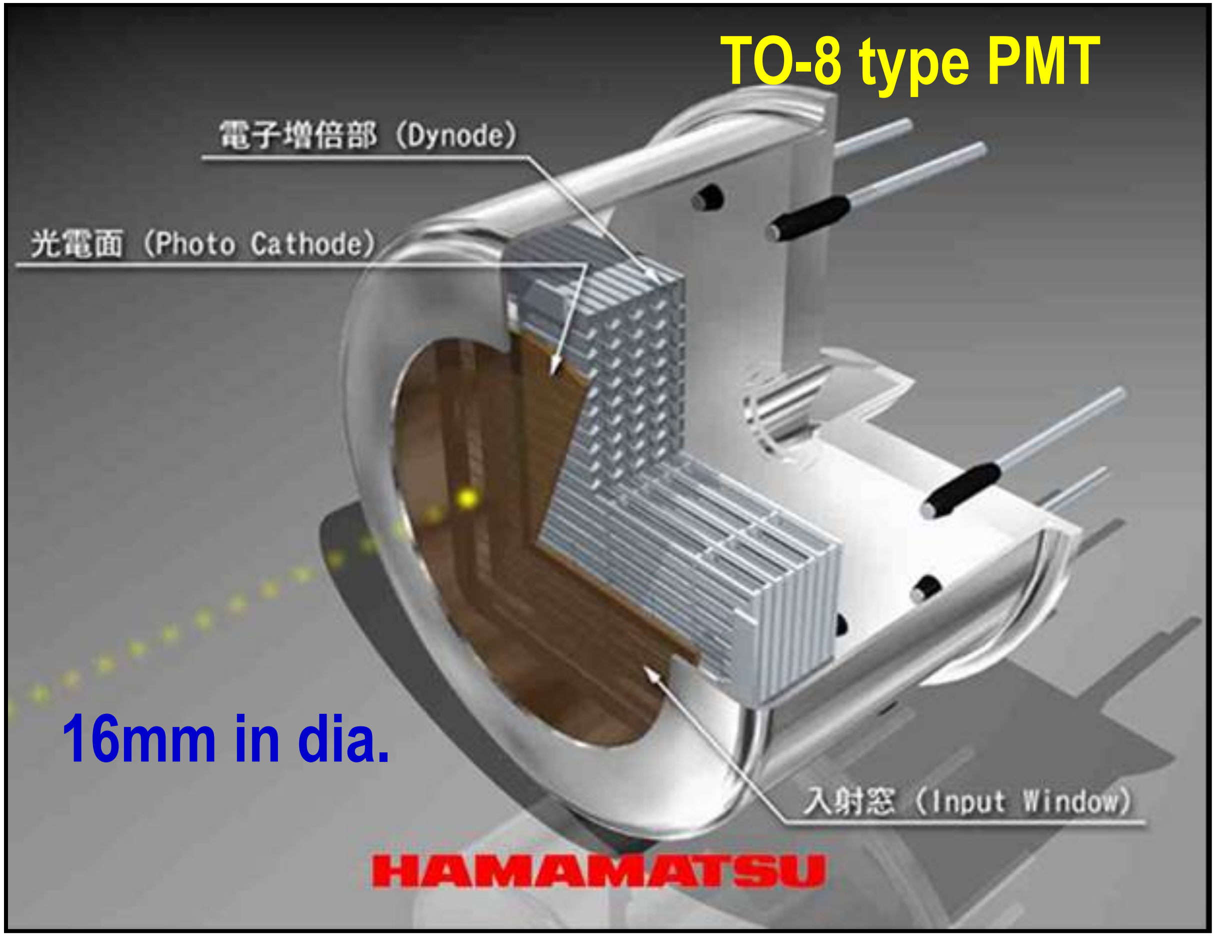
Large dynode area
Better uniformity

Metal Channel PMT

METAL CHANNEL

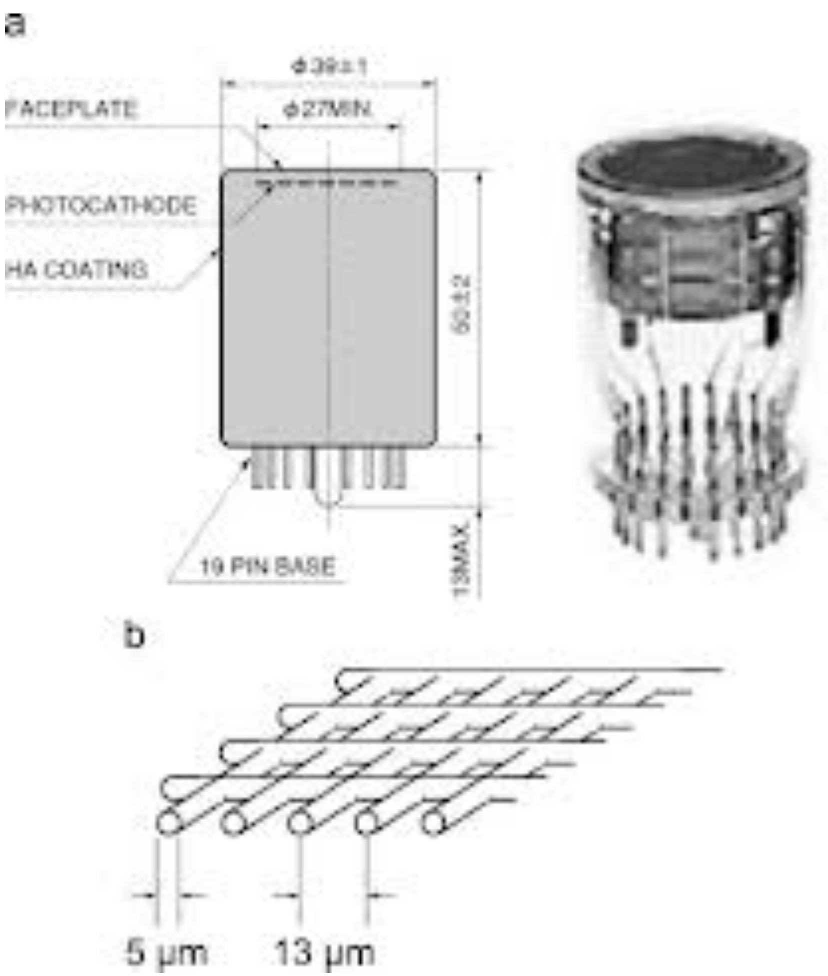


PMT with Metal Channel Dynode



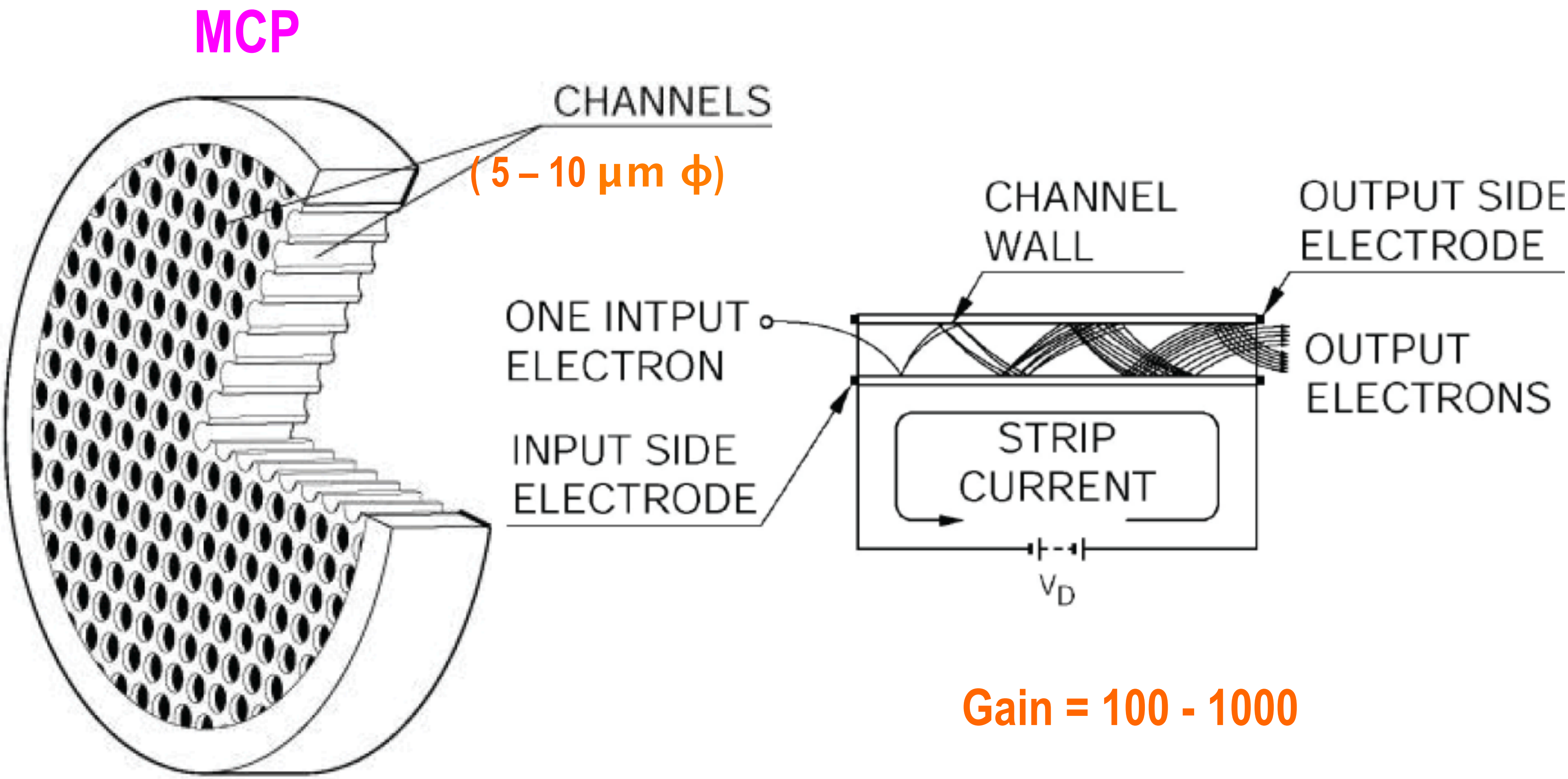
Compact
Fast time response
Position sensitive

Fine Mesh PMT



Fine Mesh

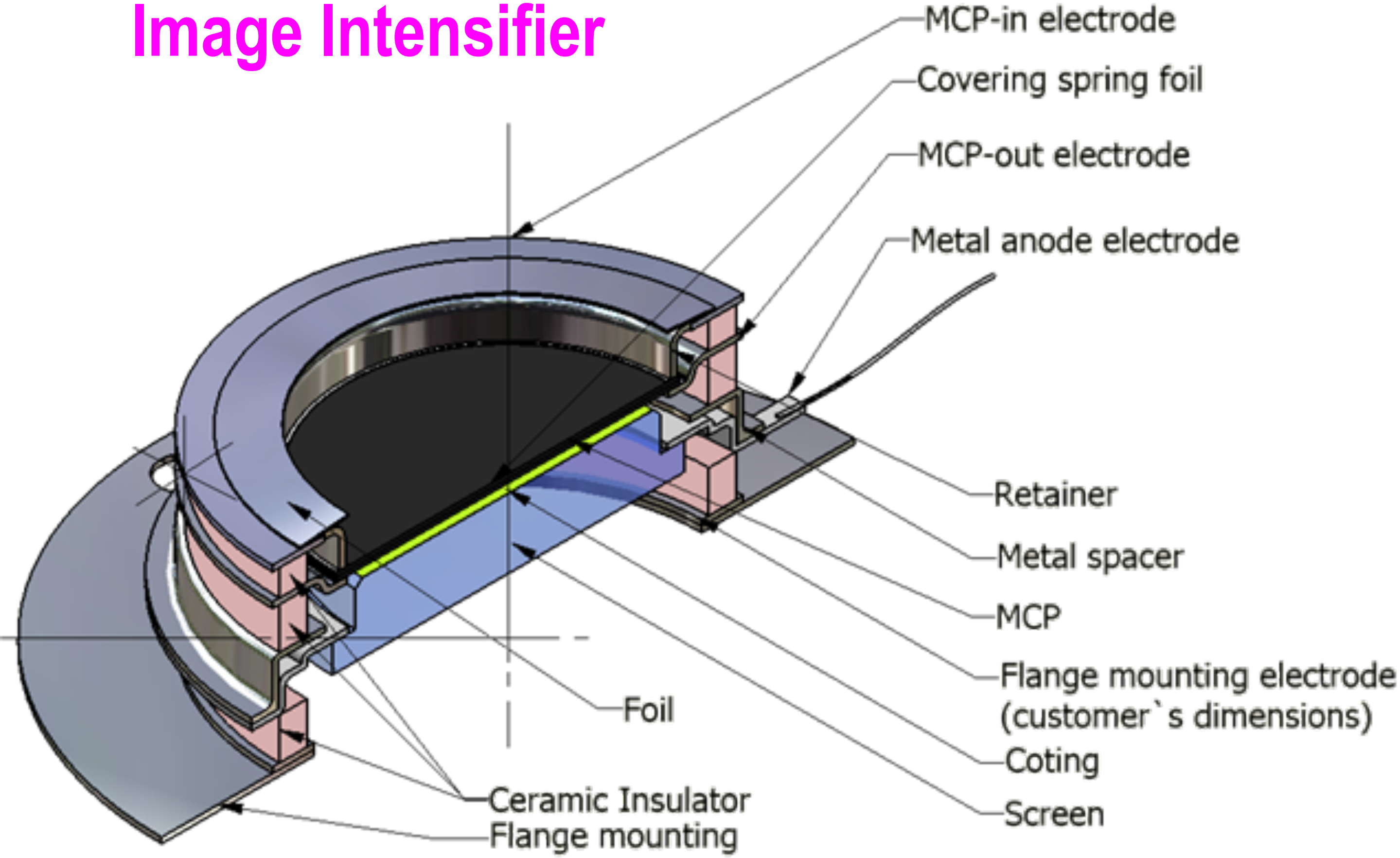
MCP (Micro Channel Plate)



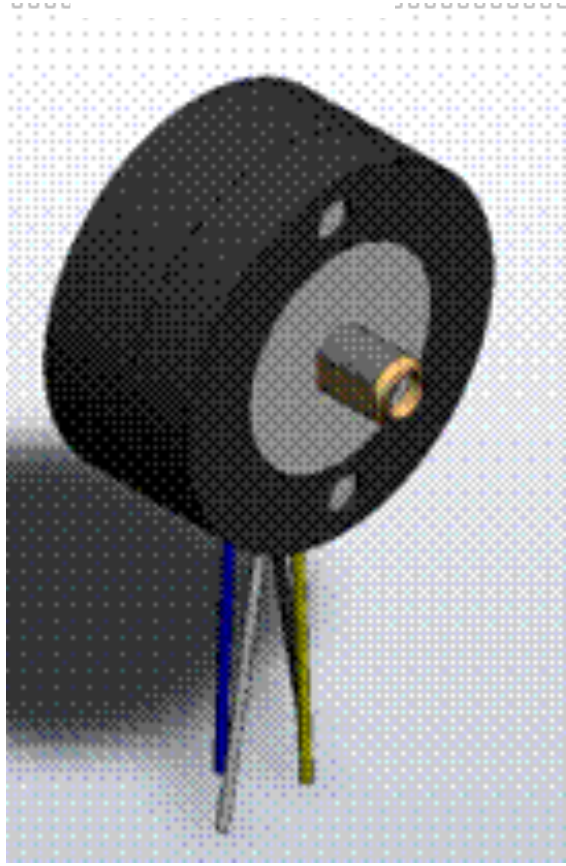
Gain = 100 - 1000

MCP PMT

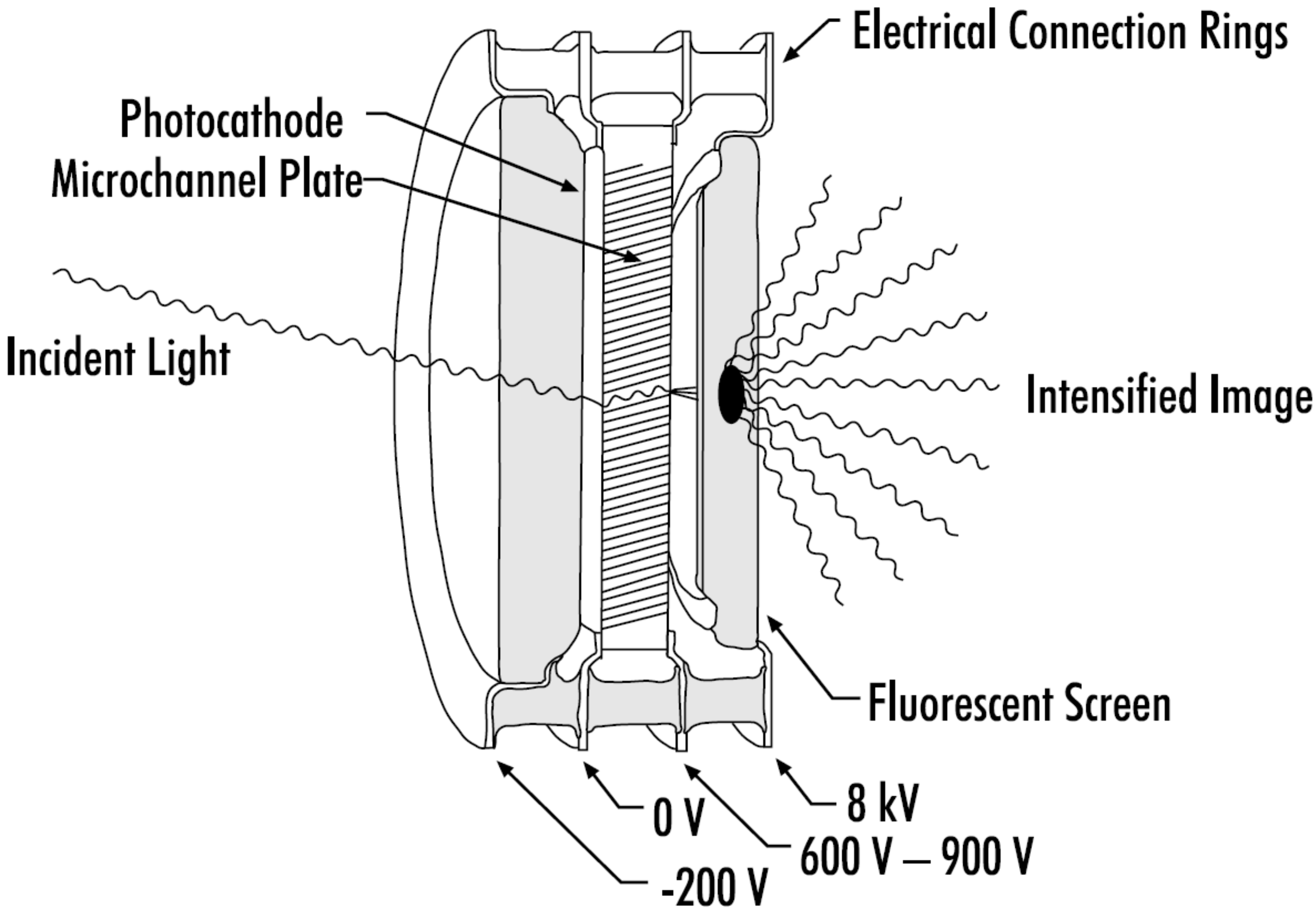
Image Intensifier



MCP PMT

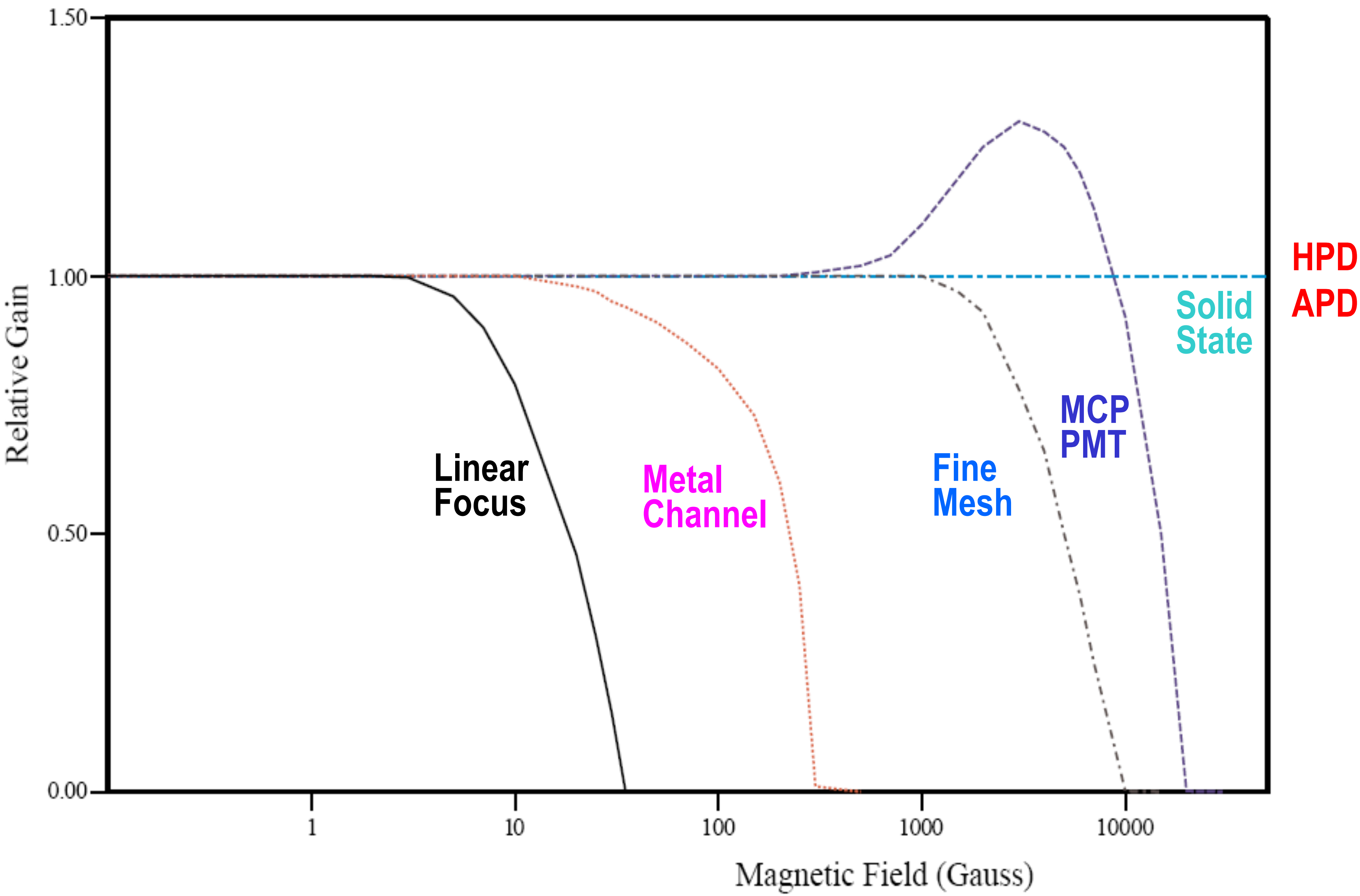


Principle of Image Intensifier



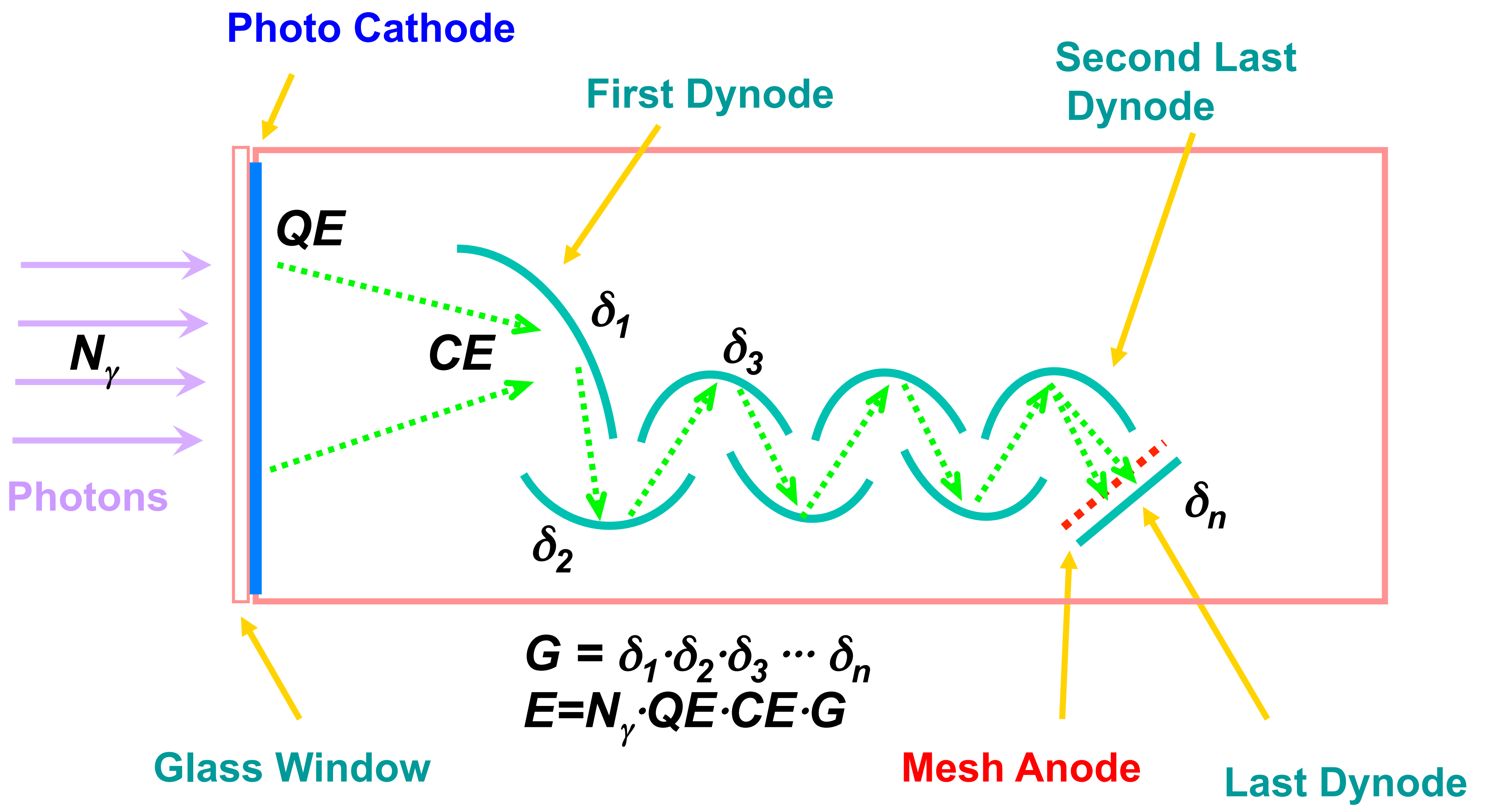
http://www.e-radiography.net/radtech/i/intensifiers.pdf

Effect of Magnetic Fields



Gain of PMT

Structure of Linear-focus PMT

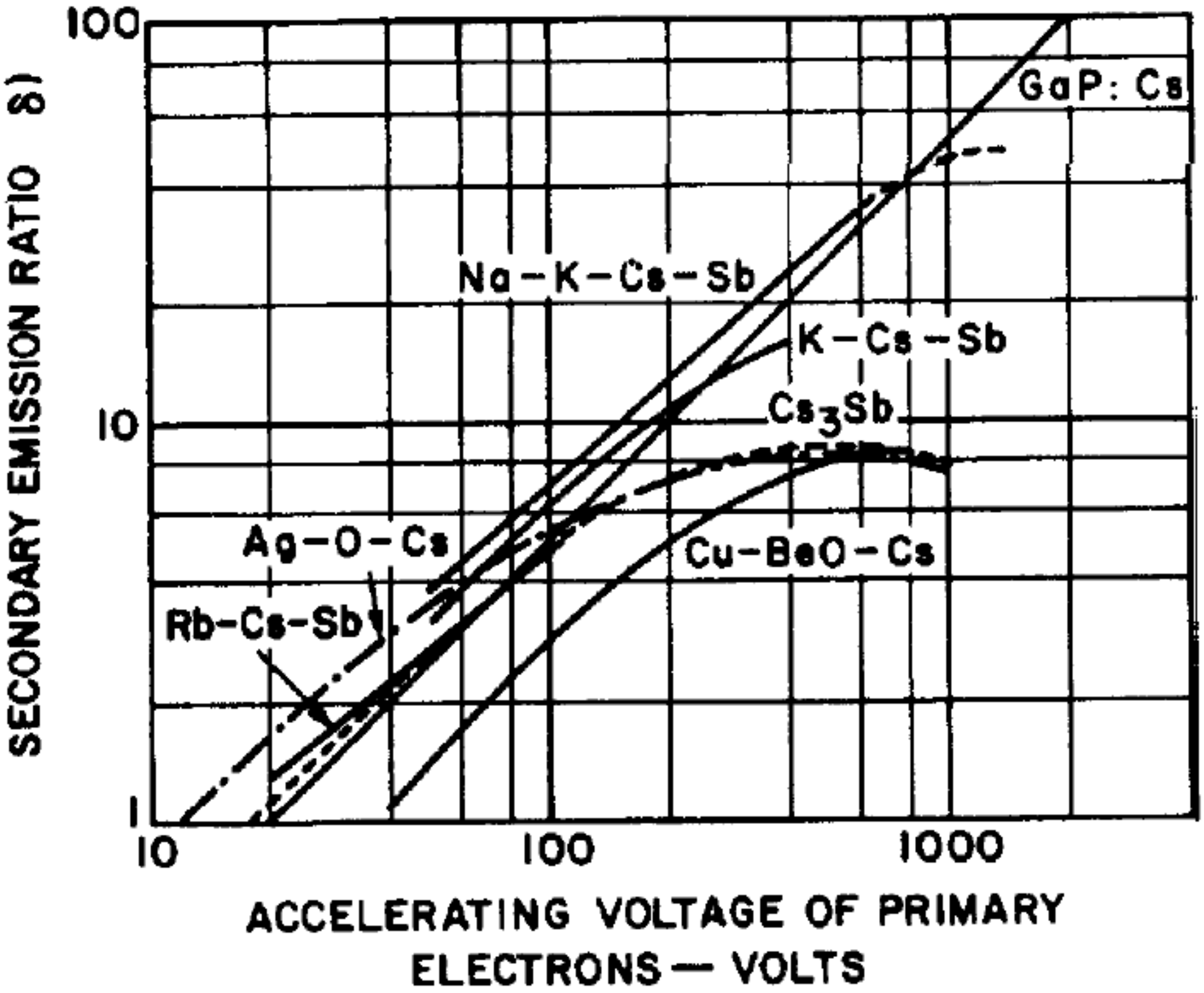


$$G = \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$$

$$E = N_\gamma \cdot QE \cdot CE \cdot G$$

Secondary electron Emission

$\delta \propto HV^{0.6}$



Gain (G_P)

- **Definition by Physicists:**

$$G_P \equiv \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$$

(δ_i = Gain of the i-th dynode)

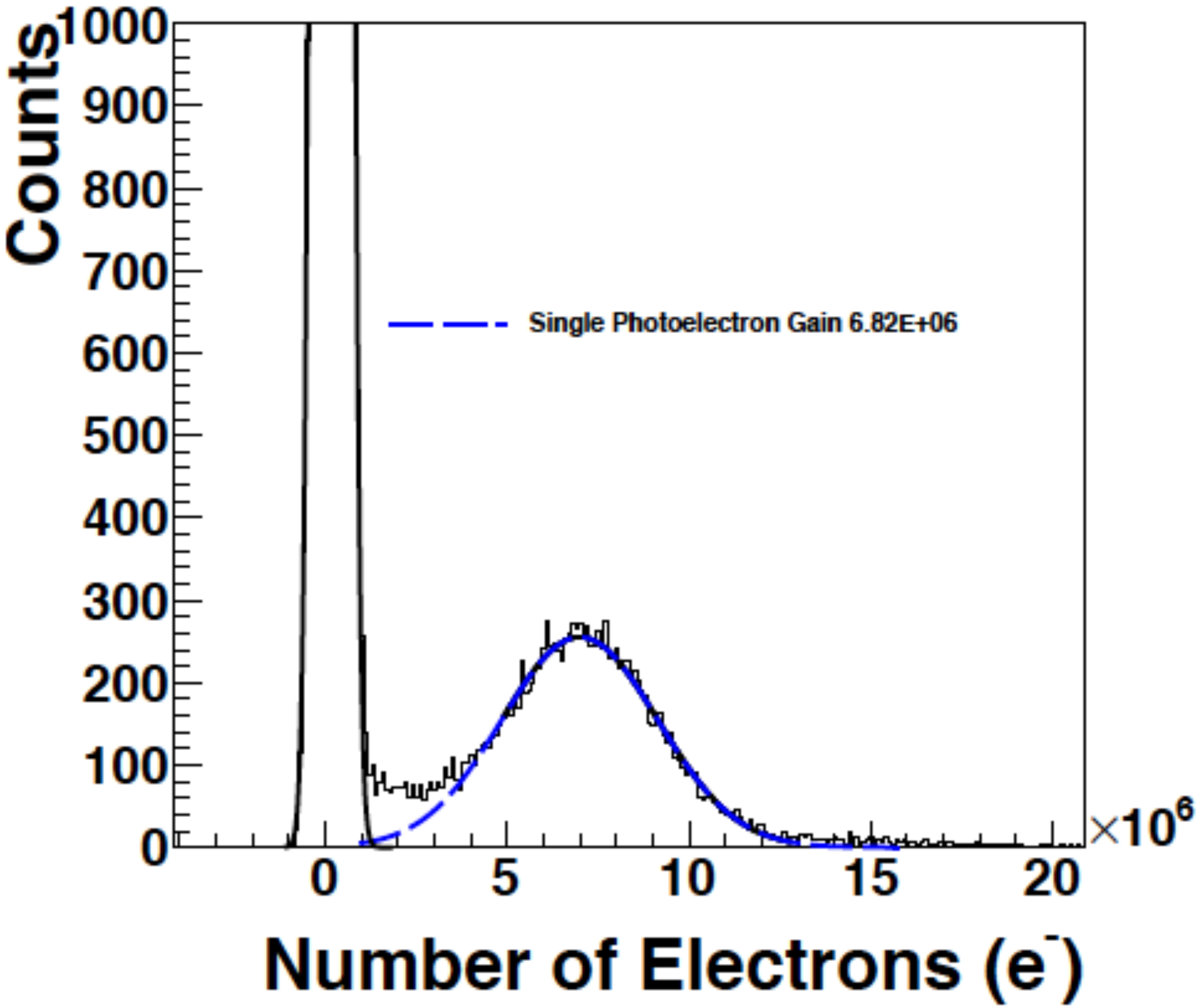
$$G_P \propto HV^{0.6n}$$

FAQ

- **How can we measure the Gain (G_P) of our definition?**

  - Use a weak pulsed light source (so that >90% pulse gives the pedestal.)
  - Measure the center of the mass of Single PE charge distribution of the Anode signal (Q_A).
  - Take the ratio of $Q_A/1.6\times10^{-19}$.

Single PE distribution



Gain (G_I)

➢ **Definition by <u>Industries</u>:**

$$G_I \equiv CE \cdot \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$$

(δ_i = Gain of the i-th dynode)

FAQ

➢ How do manufactures measure the real Gain (G_I)?

- Measure the Cathode current (I_C).
- Add 10^{-5} ND filter in front of PMT.
- Measure the Anode current (I_A).
- Take the ratio of $I_A \times 10^5 / I_C$.

$$G_I = CE \cdot G_P$$

Gain vs. Voltage Curve

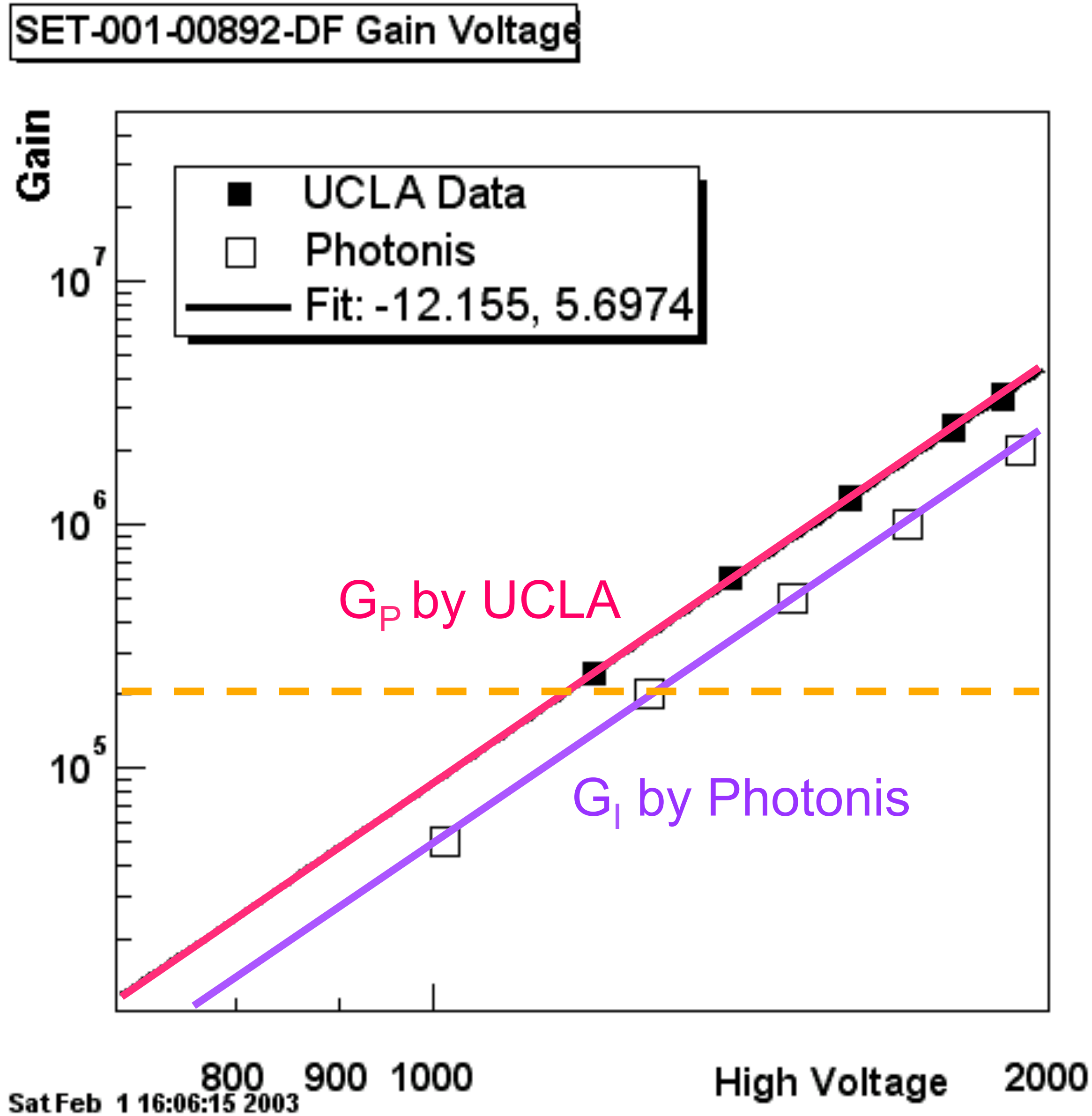
Physicists Definition:

$G_P = \delta_1 \bullet \delta_2 \bullet \ldots \bullet \delta_n$

Industries Definition:

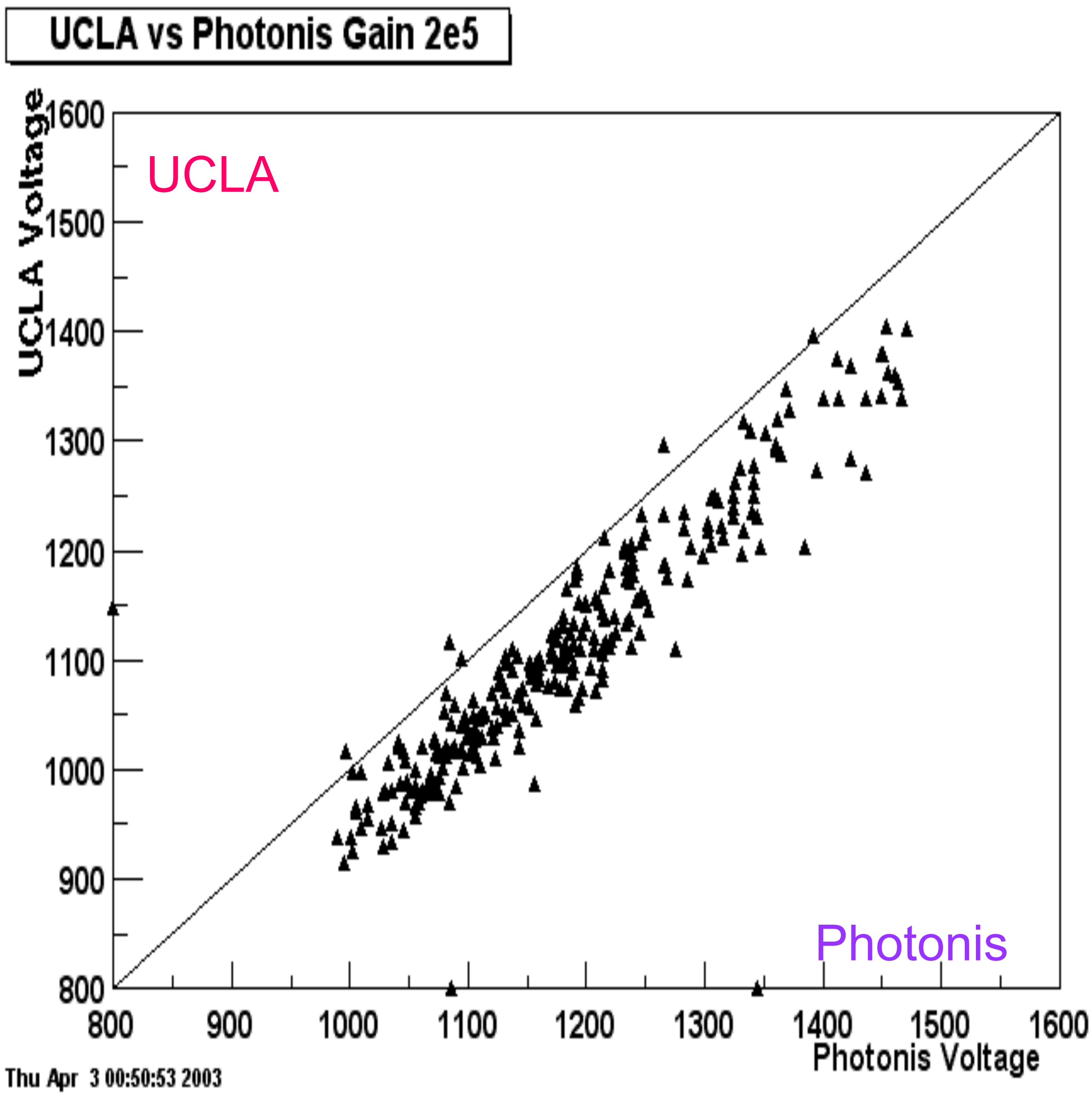
$G_I = CE \bullet \delta_1 \bullet \delta_2 \bullet \ldots \bullet \delta_n$

$CE = G_I / G_P \sim 80\%$.



270 Auger-SD PMTs: HV for $G=2\times10^5$ UCLA vs. Photonis

- HV varies from PMT to PMT.
- Photonis is Higher than UCLA (due to CE).
- CE varies from PMT to PMT.



FAQ

- **Why is the Gain so different from PMT to PMT at the fixed HV?**

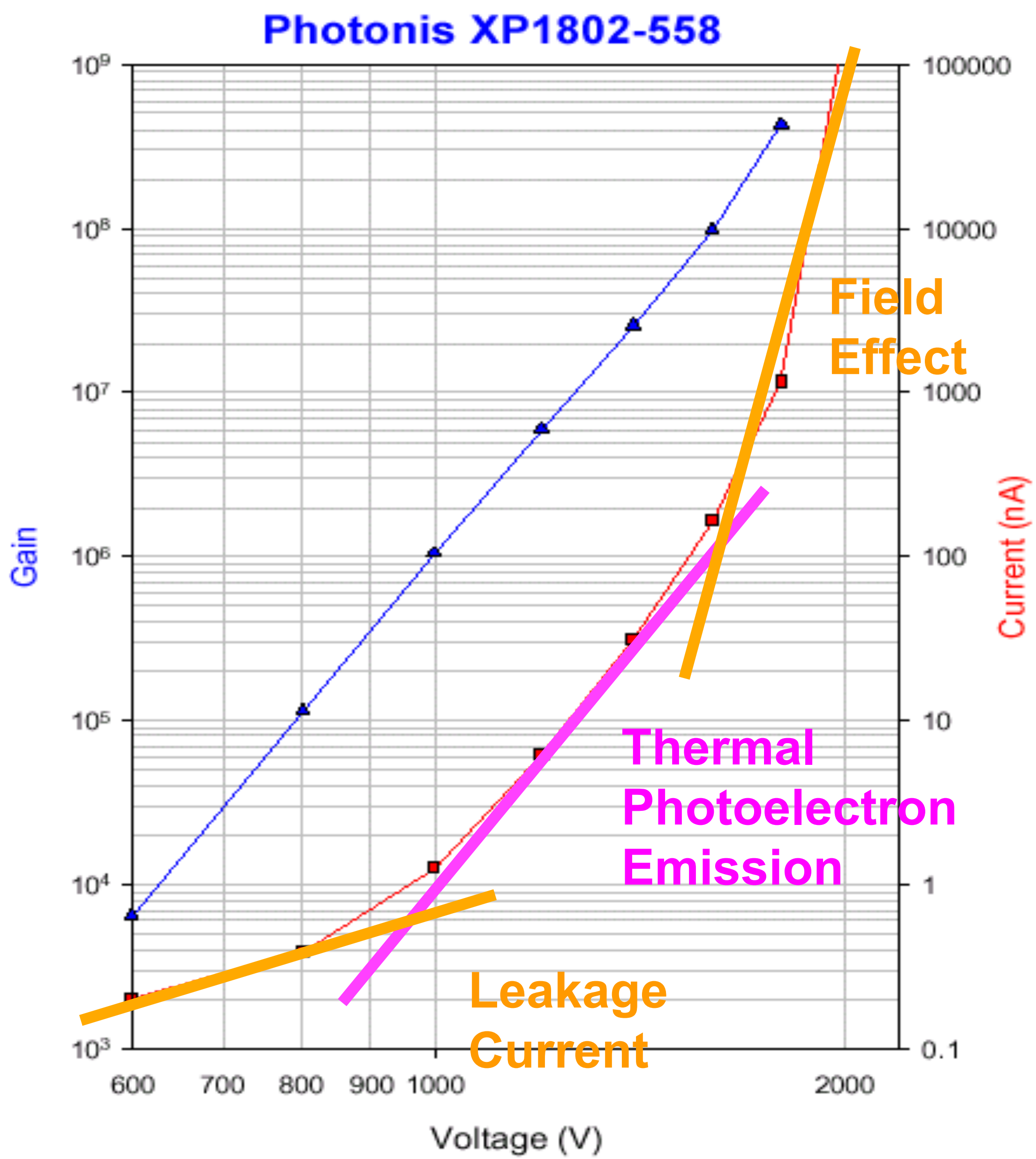
  - **At given HV, each δ may be ±10% different.**
  - **Then, Gain could be an order of magnitude different. ($G = \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$)**

FAQ

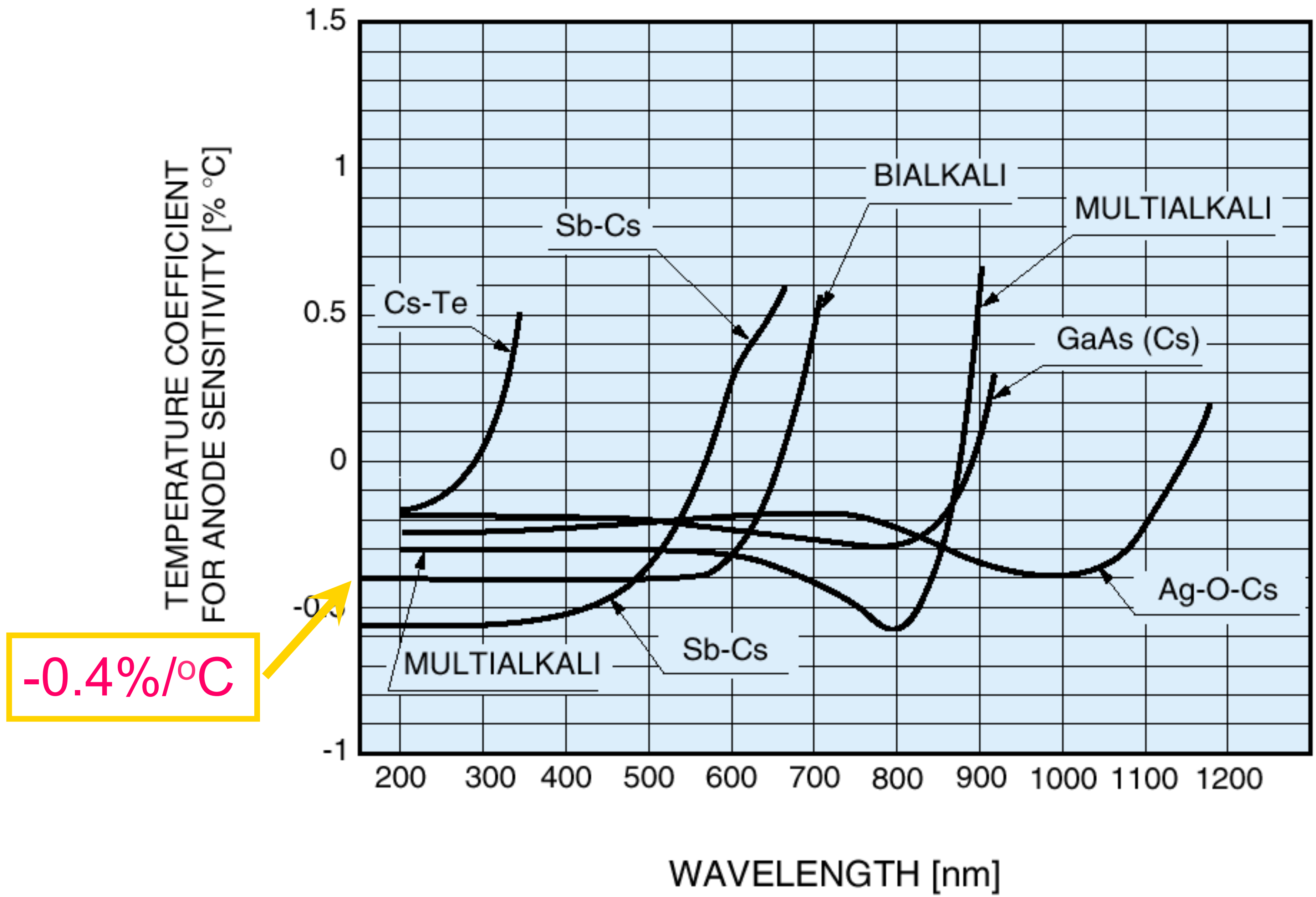
- **What is the maximum allowed HV for stable PMT operation?**

  - **It can be checked by Dark Current behavior.**

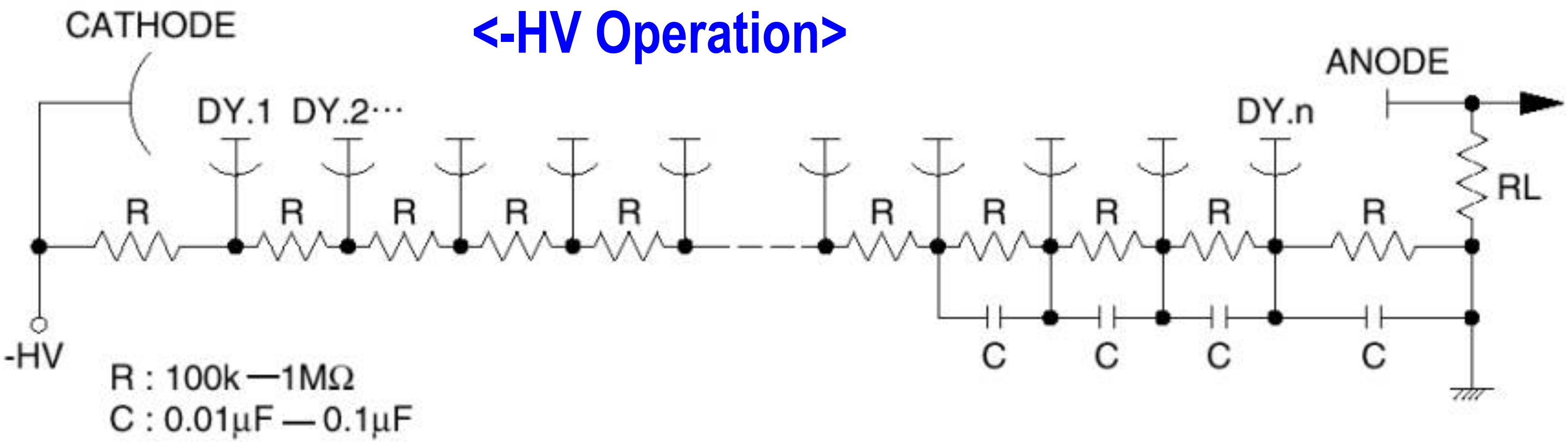
Gain and Dark Current vs. HV



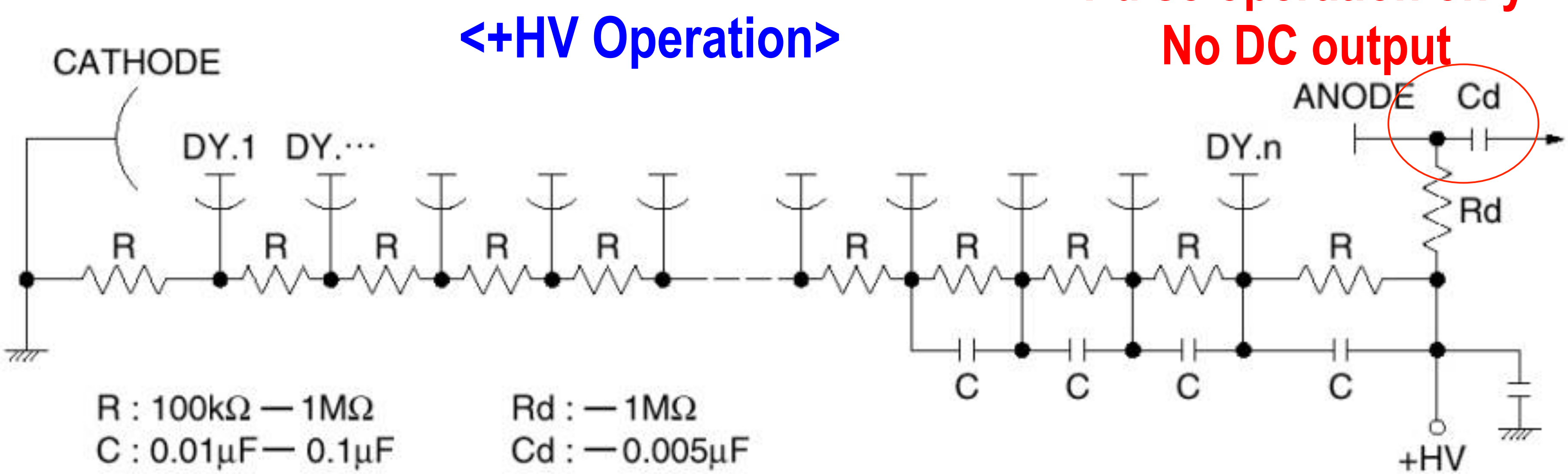
Temperature Dependence of Anode Sensitivity



Two Types of Voltage Divider

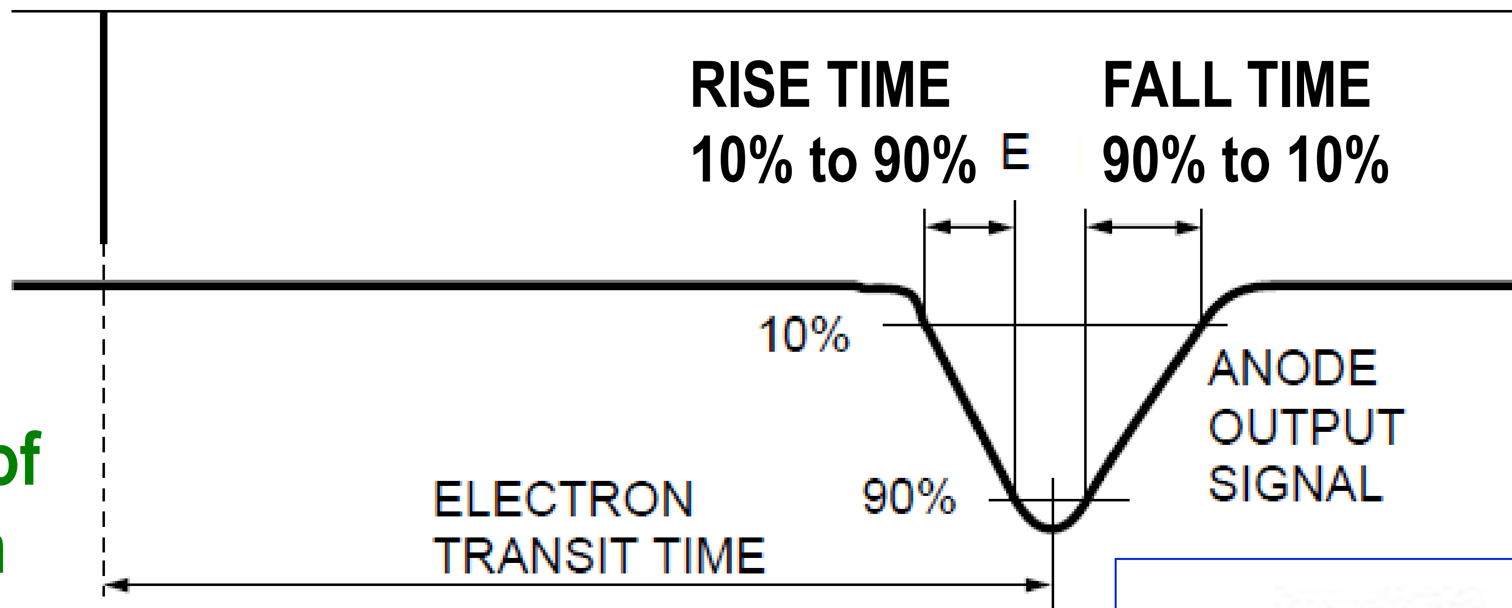


Pulse operation only
No DC output



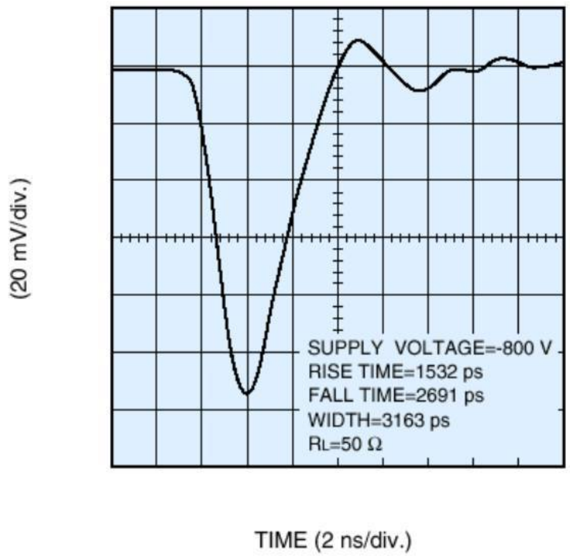
Time Response

Time Response



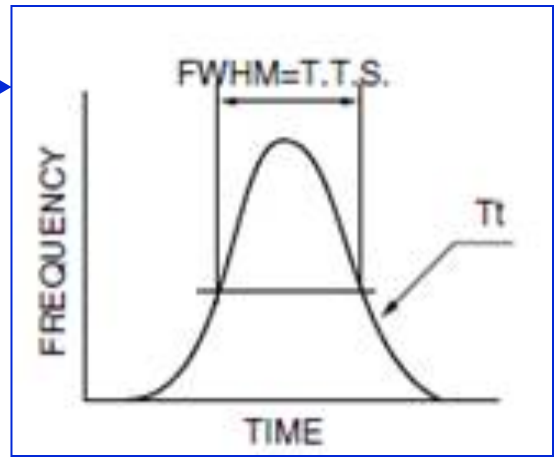
Transit Time

Example of Waveform



Rise : 1.5 ns

Fall : 2.7 ns

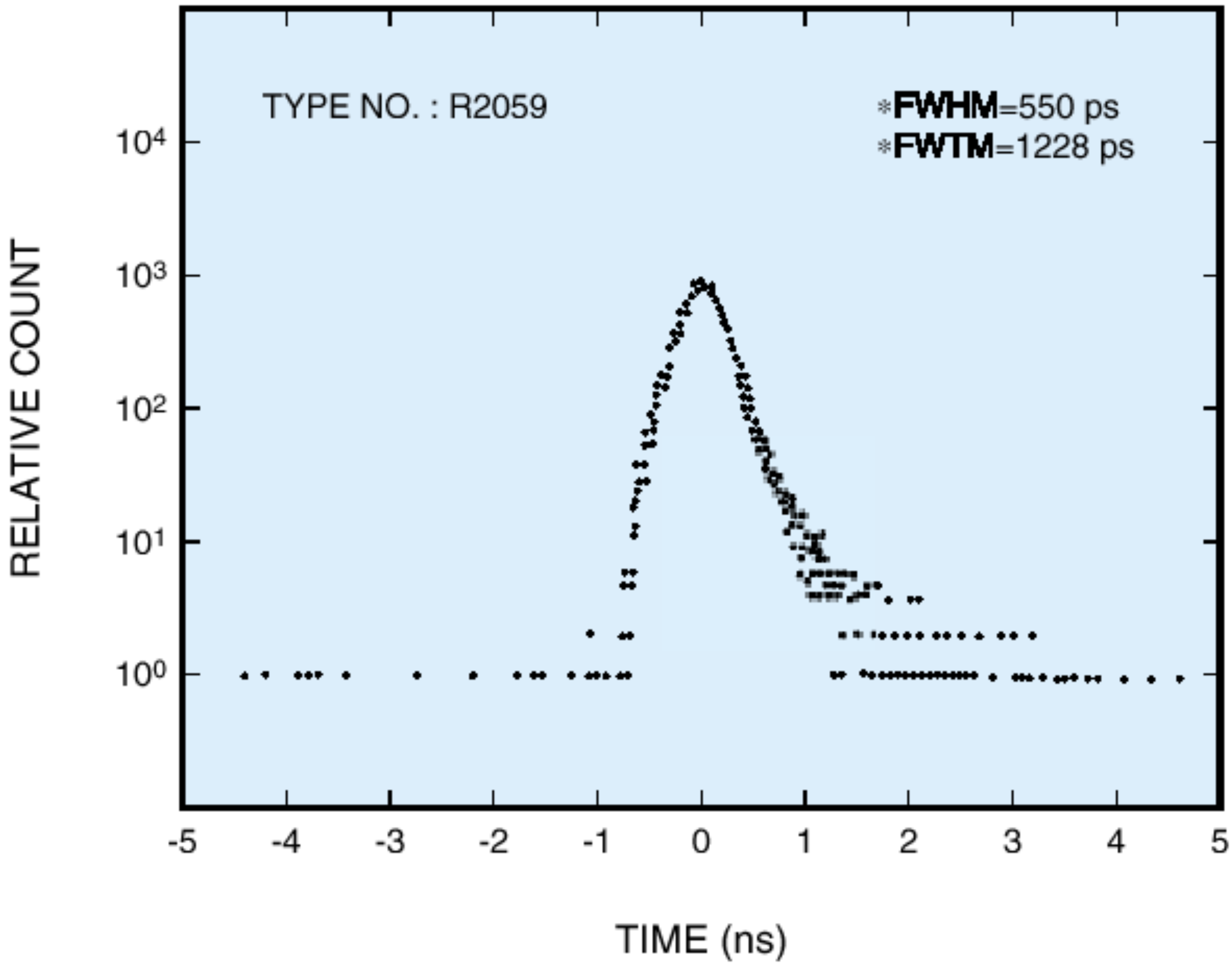


TTS

Transit Time Spread

(Variation of Transit Time)

Typical TTS (Transit Time Spread)

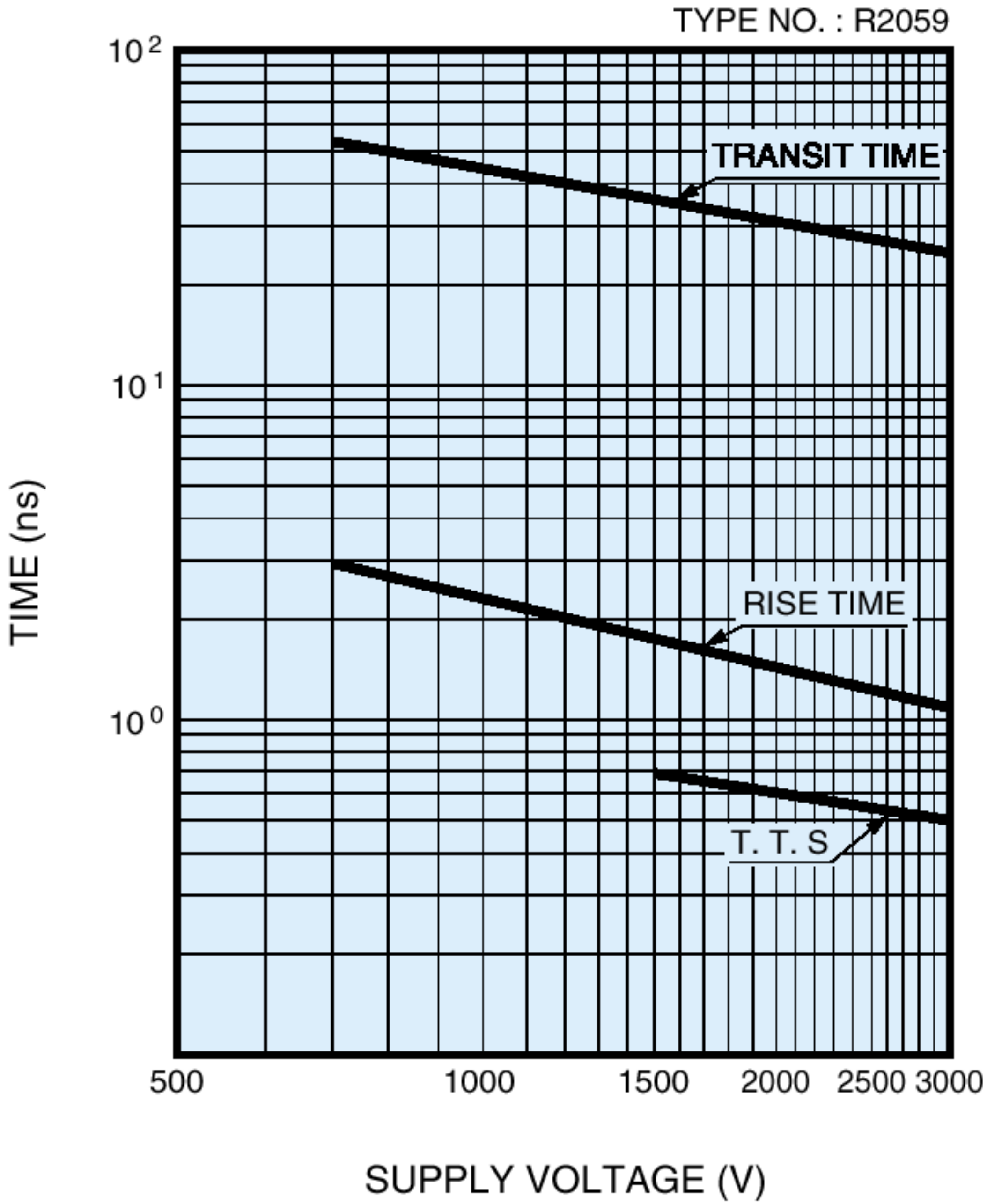


Transit Time vs. HV

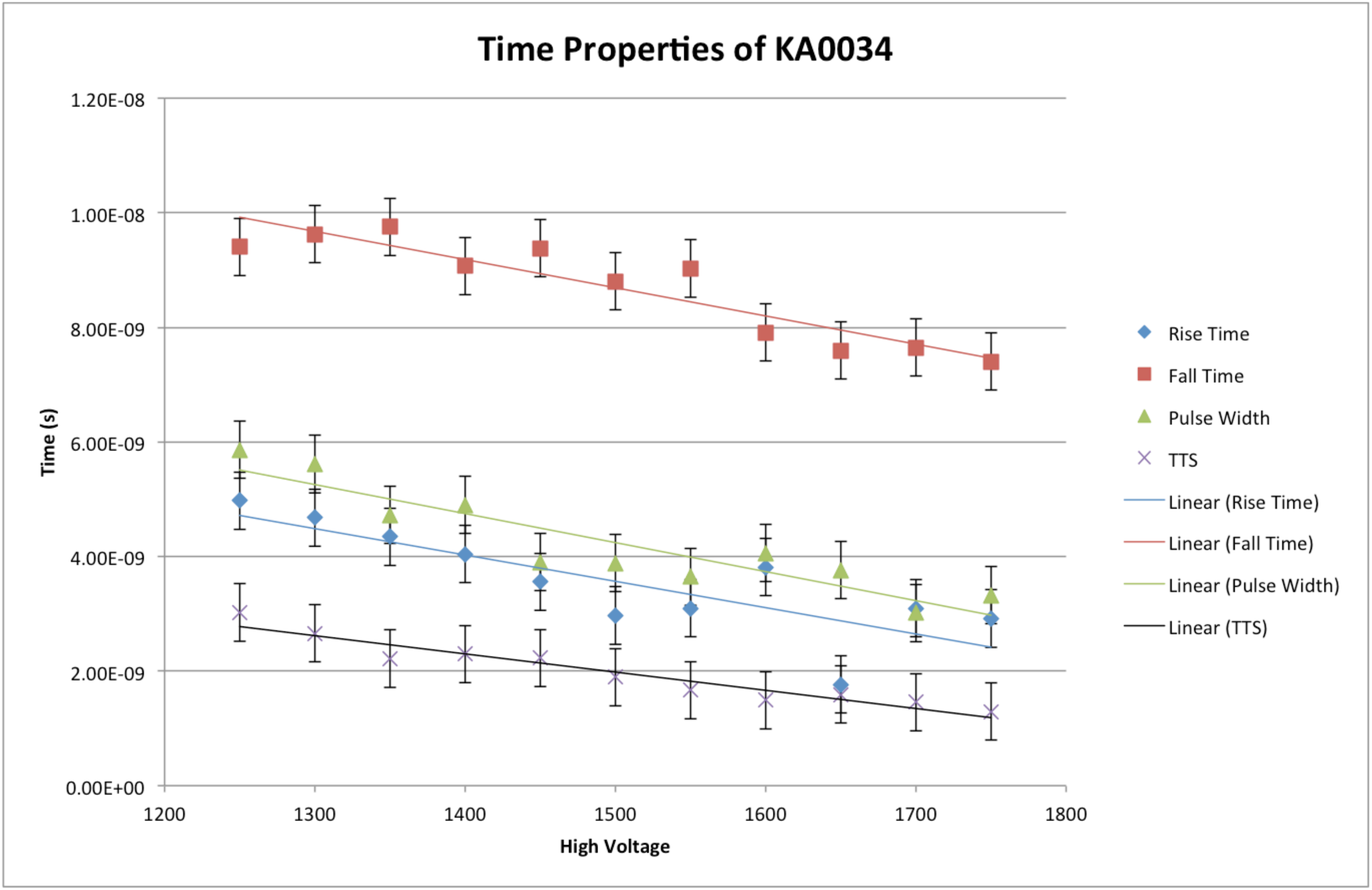
Higher Voltage

⇓

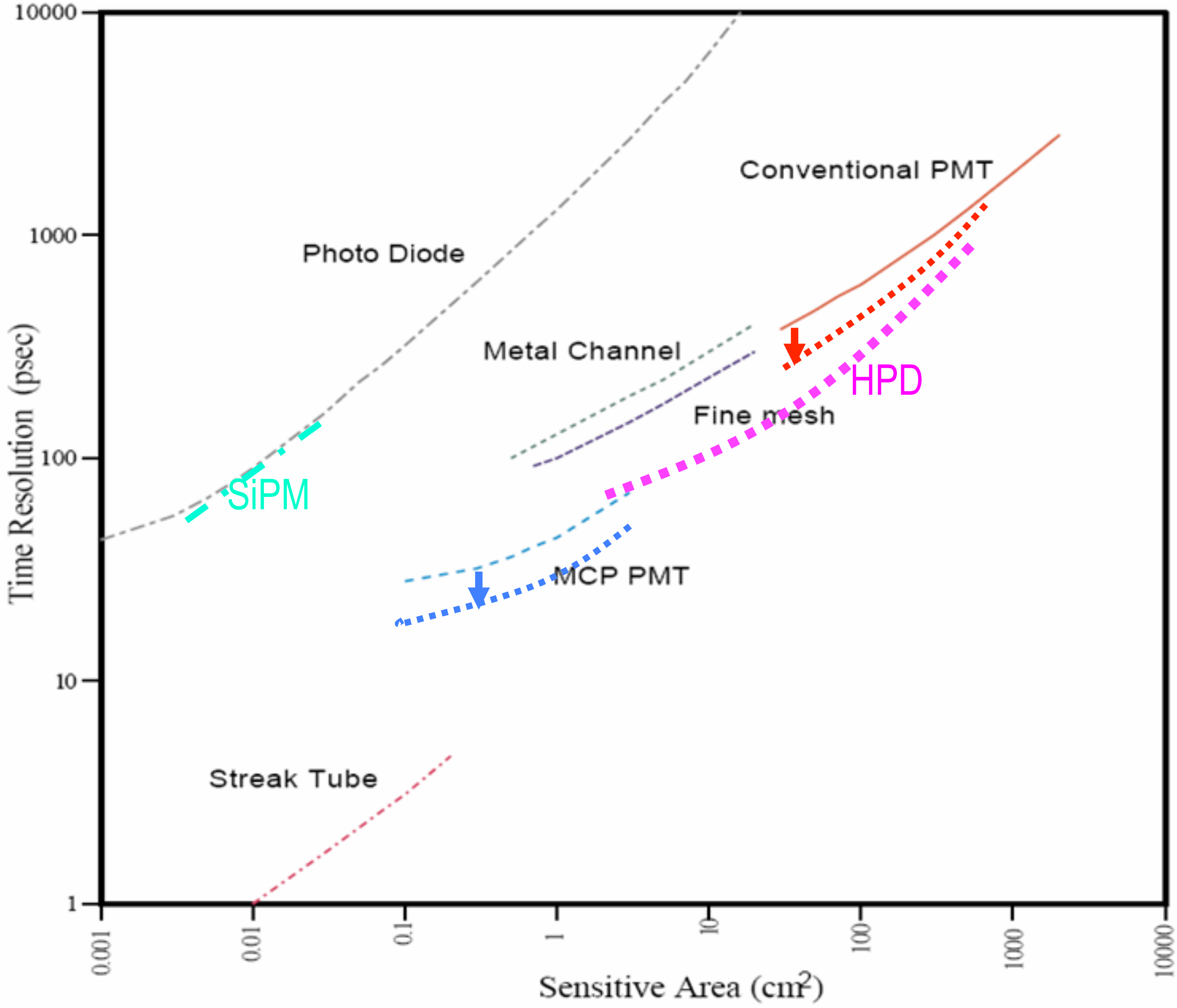
Faster Transit Time



Time Properties (R11410)



Time Resolution vs. Sensitive Area



Imperfect Behavior of PMT

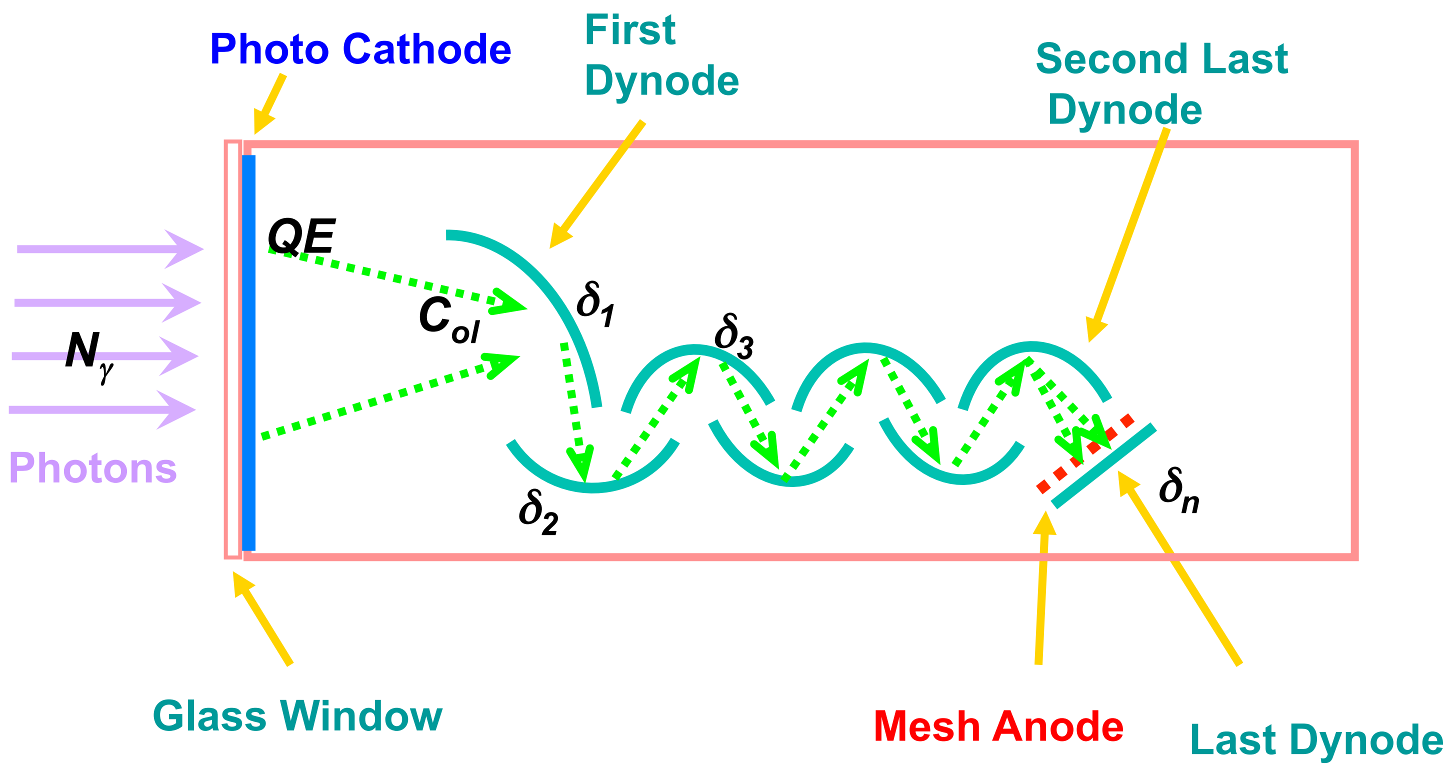
Uncertainties Specific to PMTs

- PMTs are not perfect. There are many issues to be concerned:
  - Non Linearity
  - Cathode and Anode Uniformity
  - Effect of Magnetic Field
  - Temperature Dependence
  - Dark Counts
  - After Pulse
  - Rate Dependence
  - Long-term Stability

Linearity

PMT Non Linearity

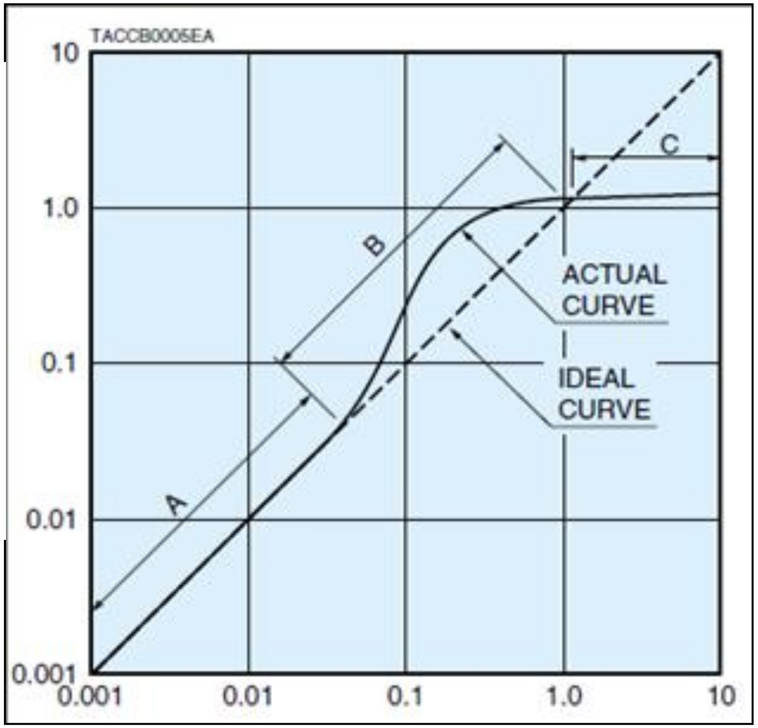
- Non Linearity is the effect of the space charge mainly between the last and the second last dynode.



Pulse Linearity

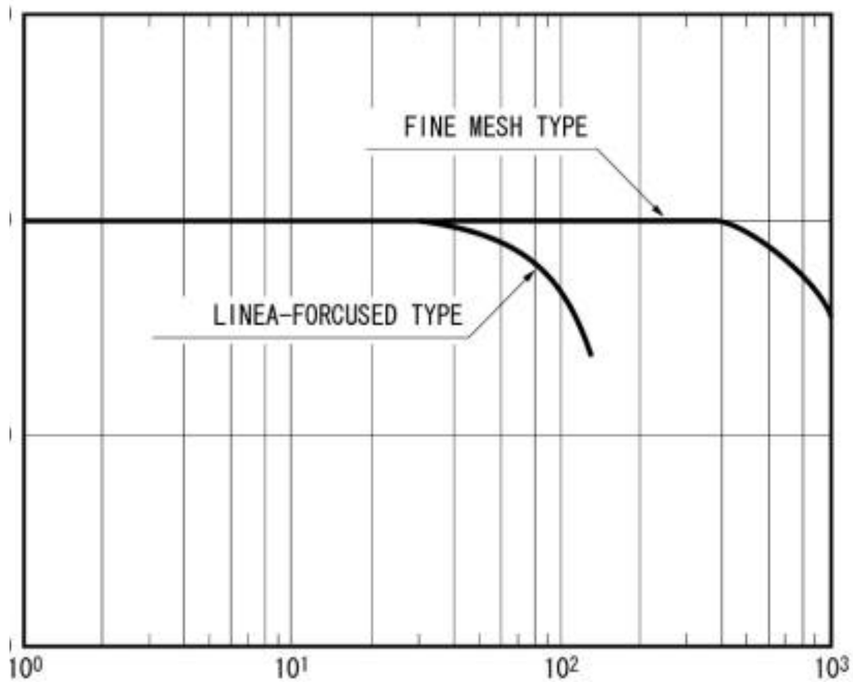
What is Pulse Linearity ?
Relation between radiation energy and PMT output.

Radiation Energy
Light Intensity



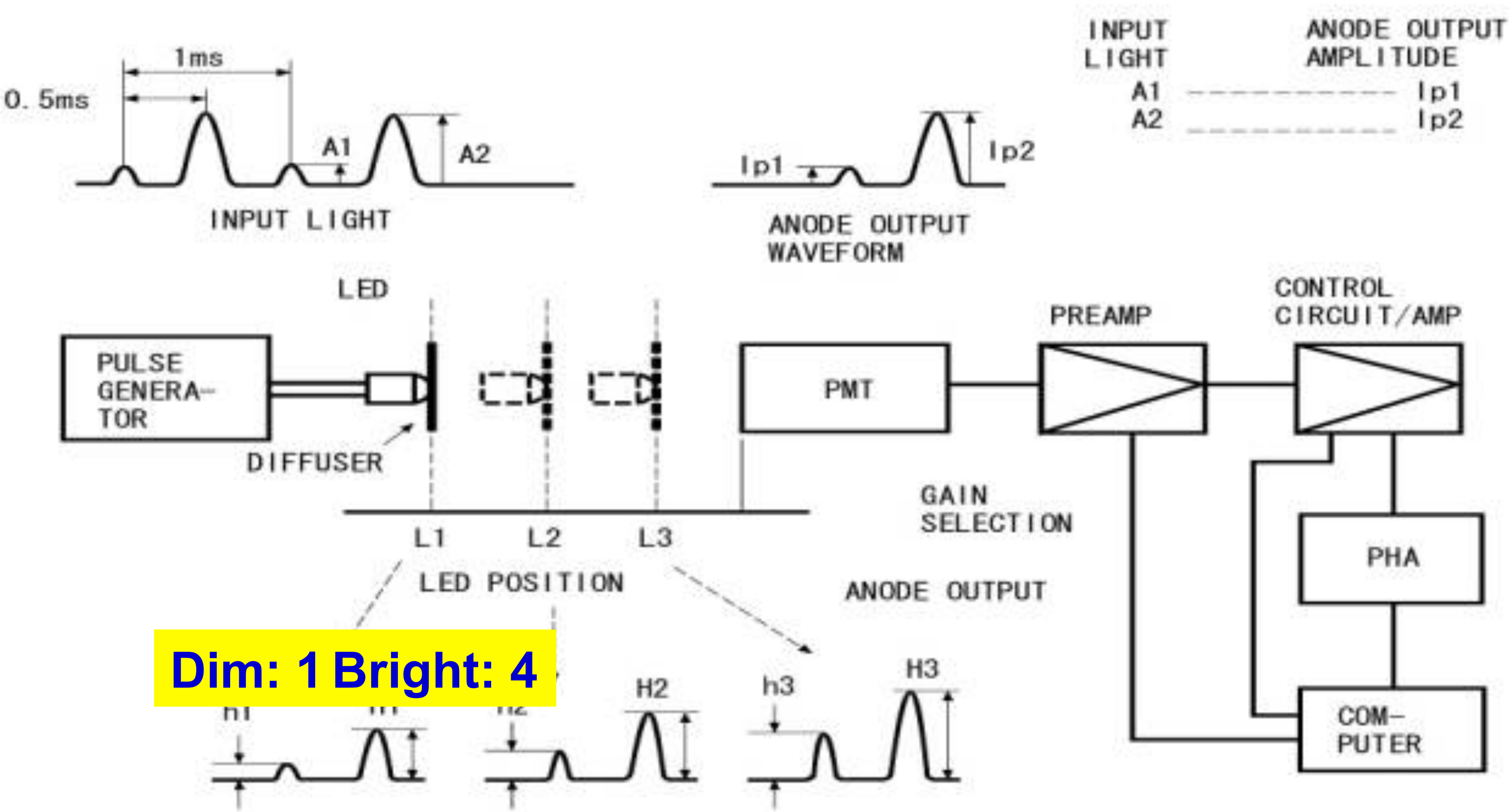
PMT output

Deviation from ideal line (%)



PMT output / peak current (mA)

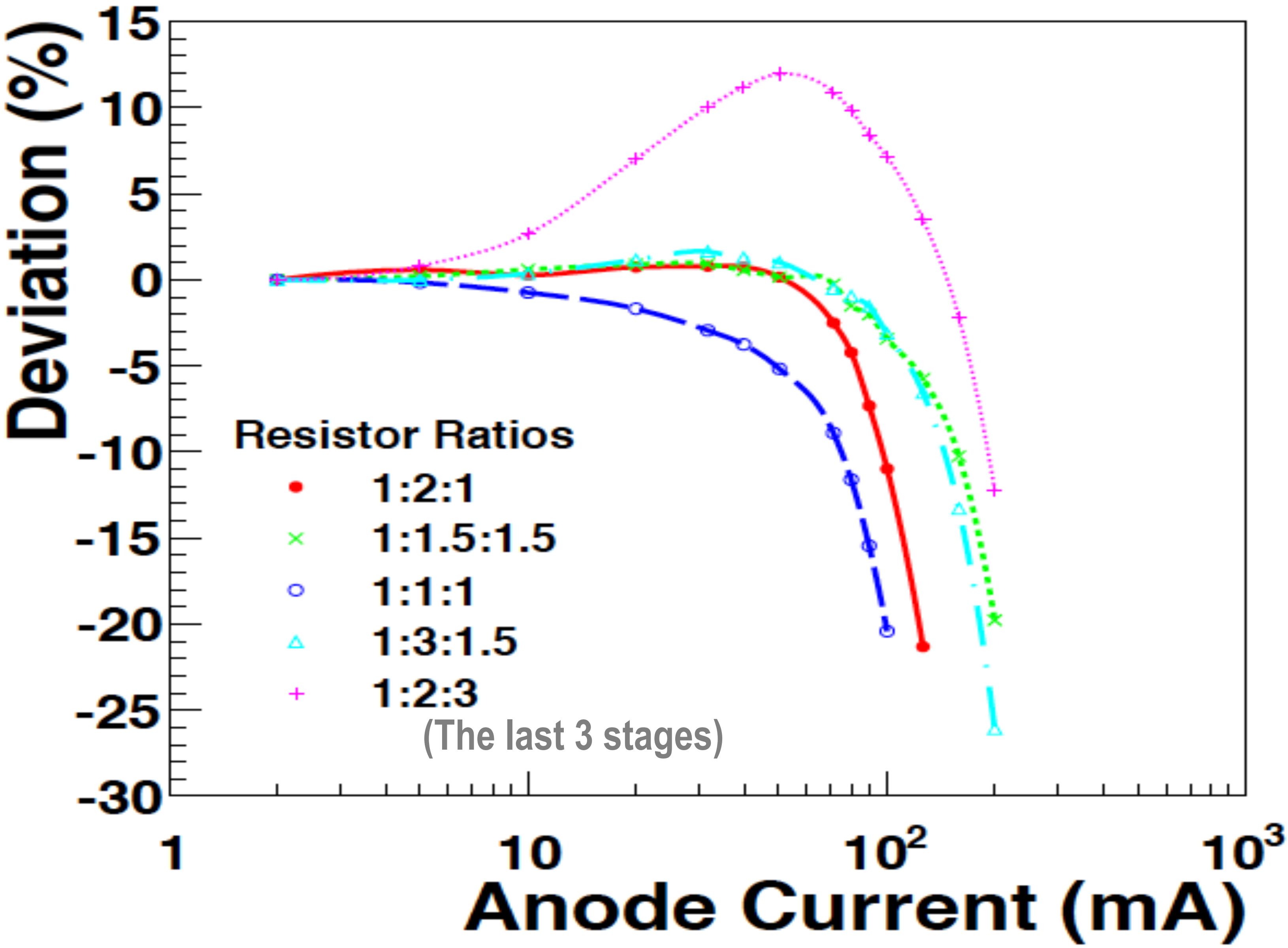
Pulse Linearity



Dim: 1 Bright: 4

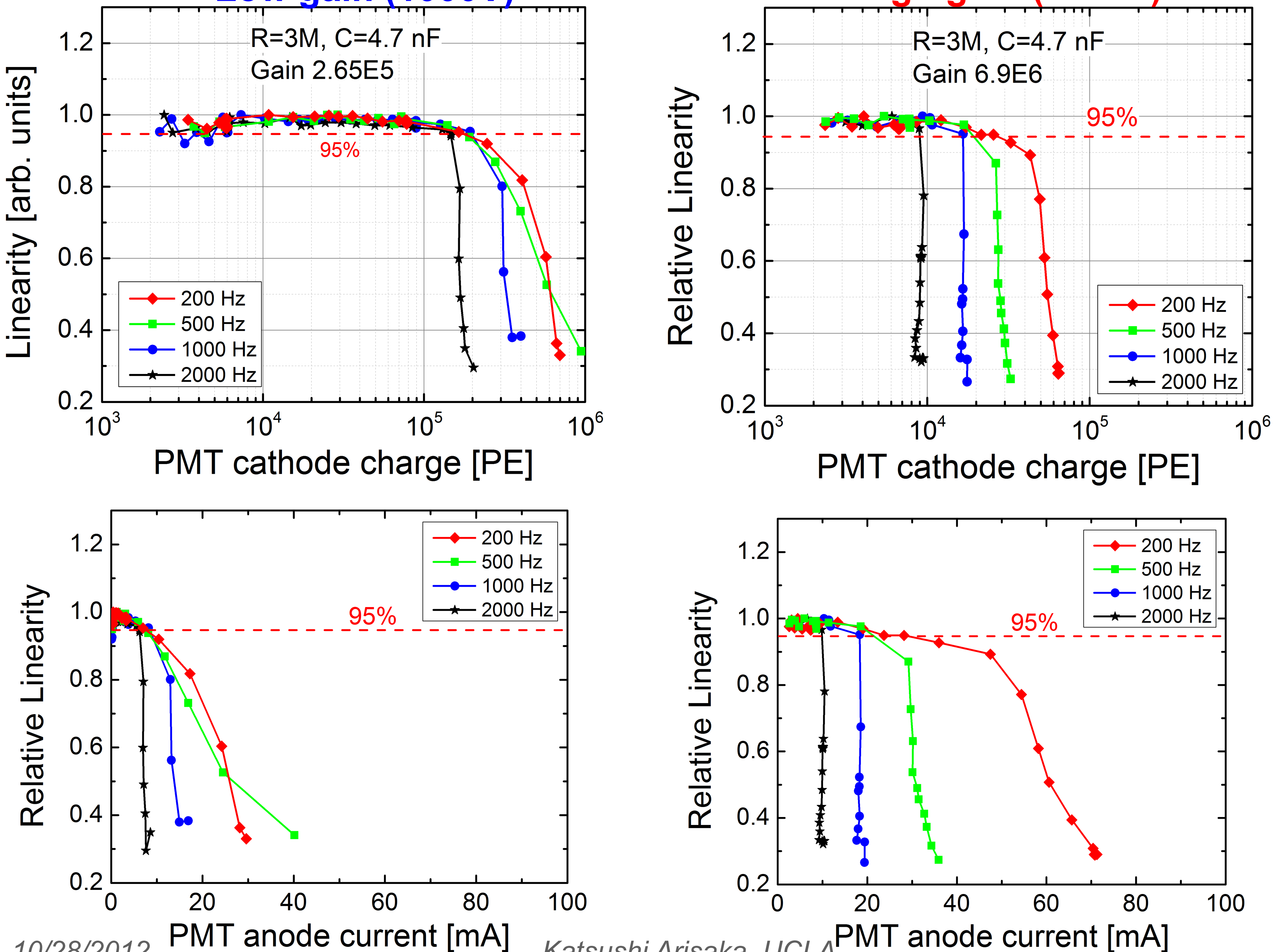
Block Diagram for Double-Pulsed Mode

Optimization of Anode Pulse Linearity



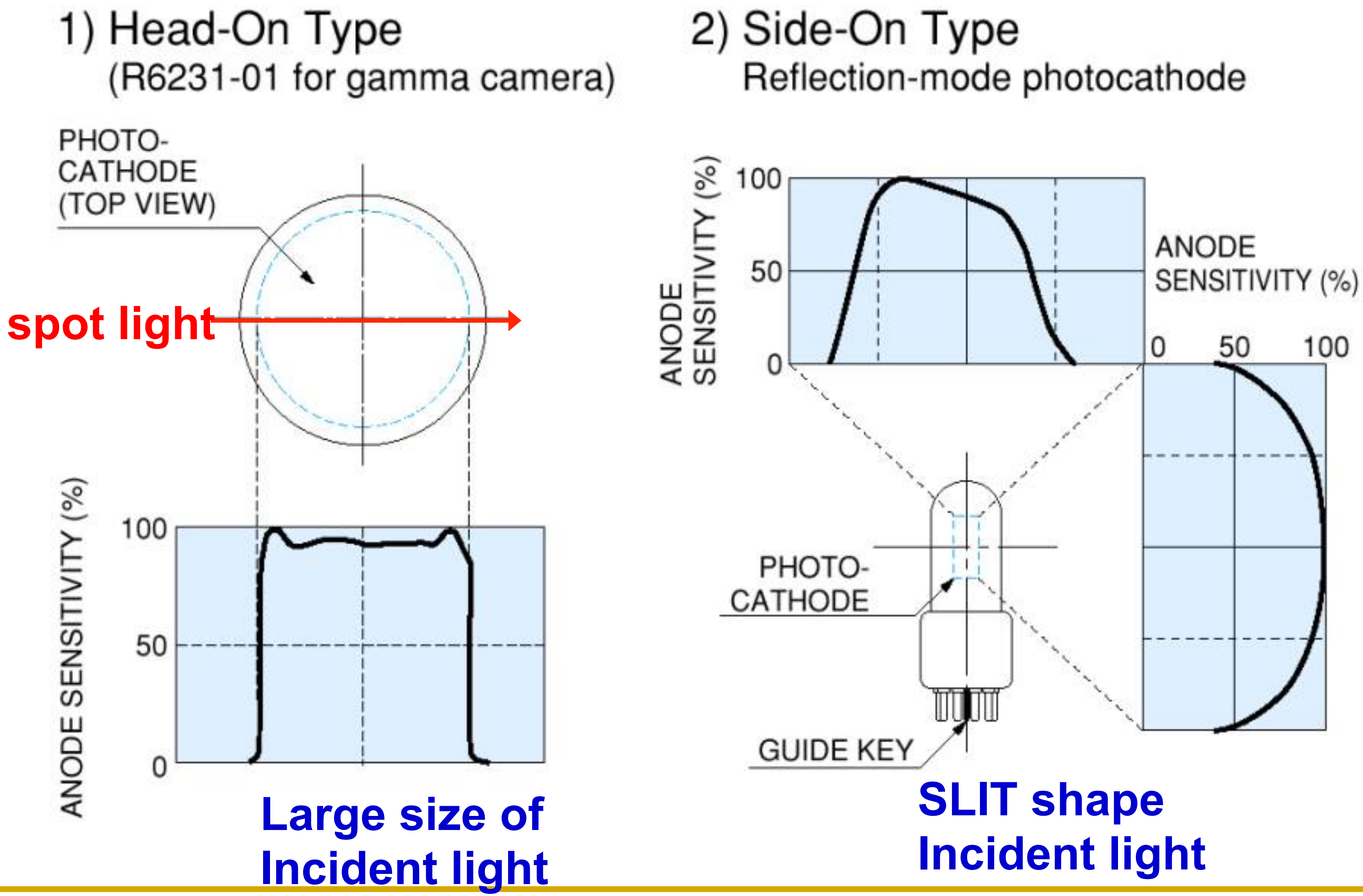
Linearity at different gains

Low gain (1000V) **High gain (1500V)**

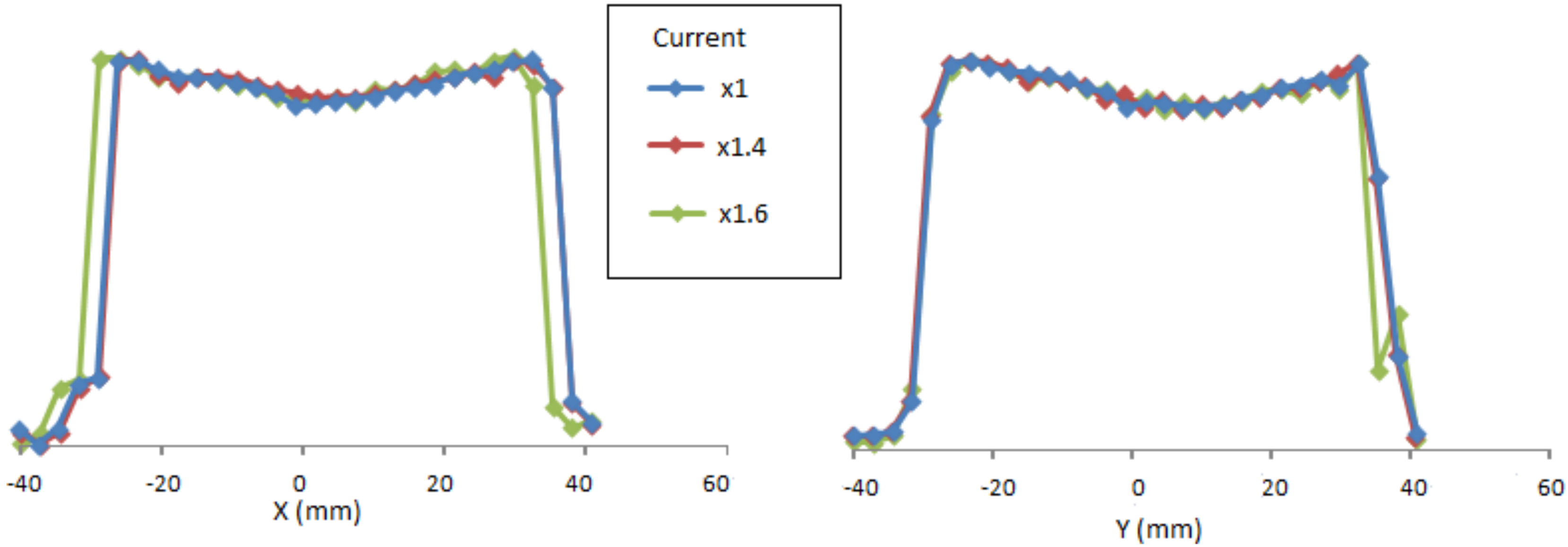


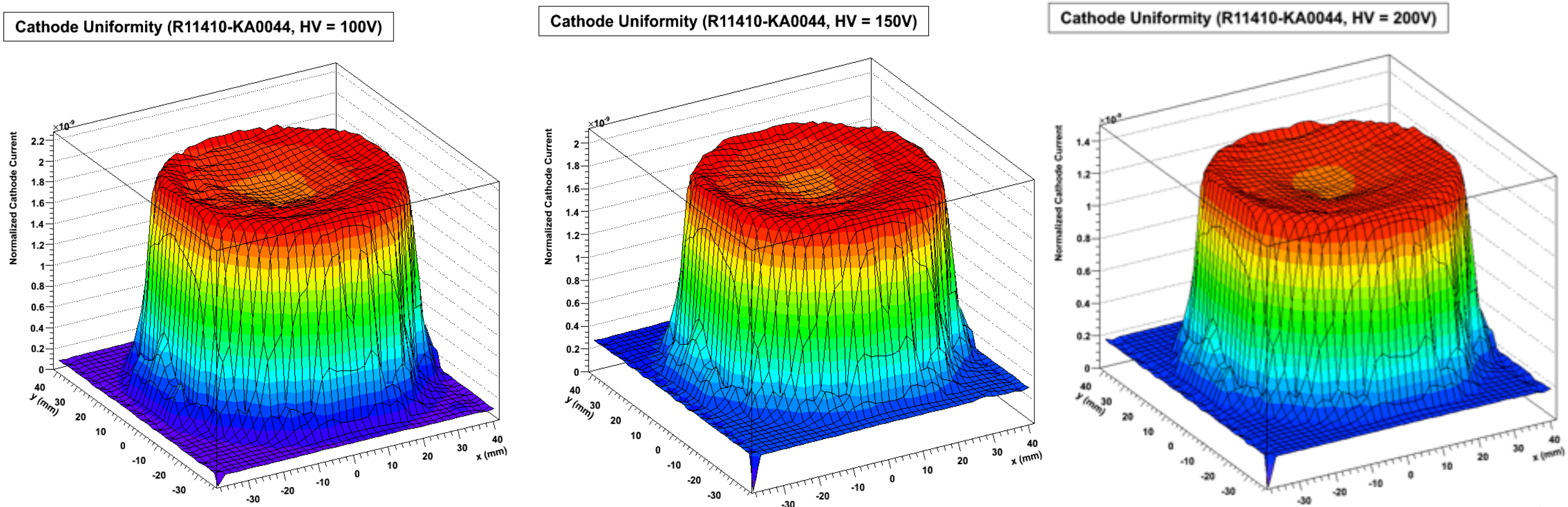
Uniformity

Anode Uniformity

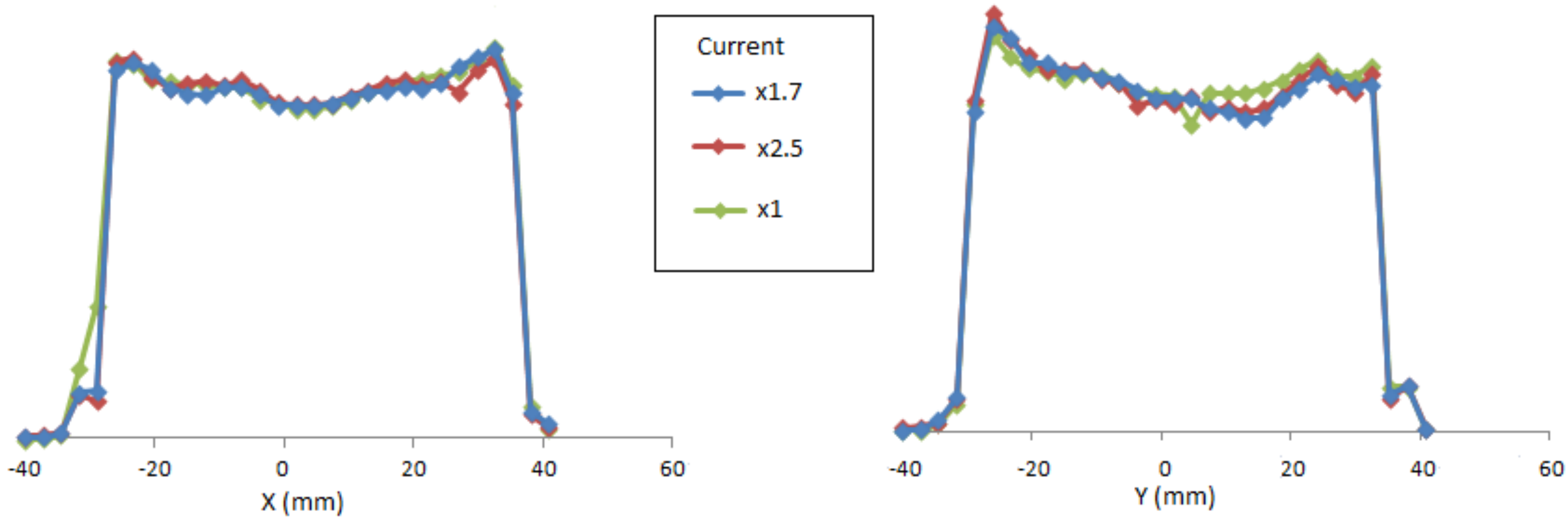


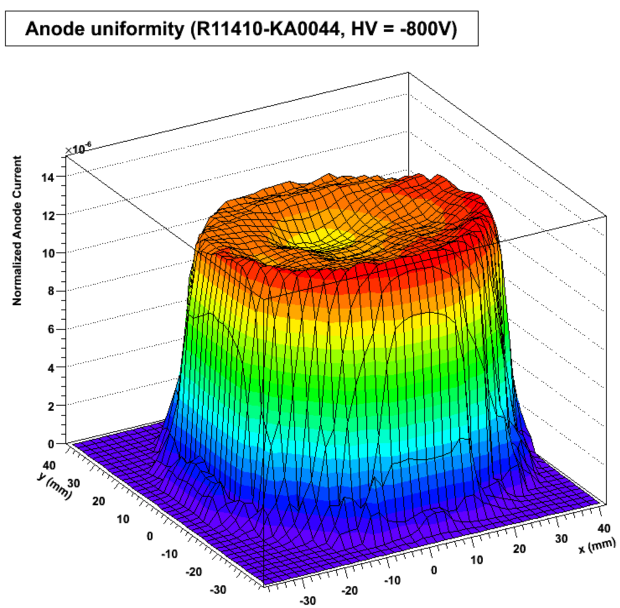
Cathode Uniformity (3 inch PMT)

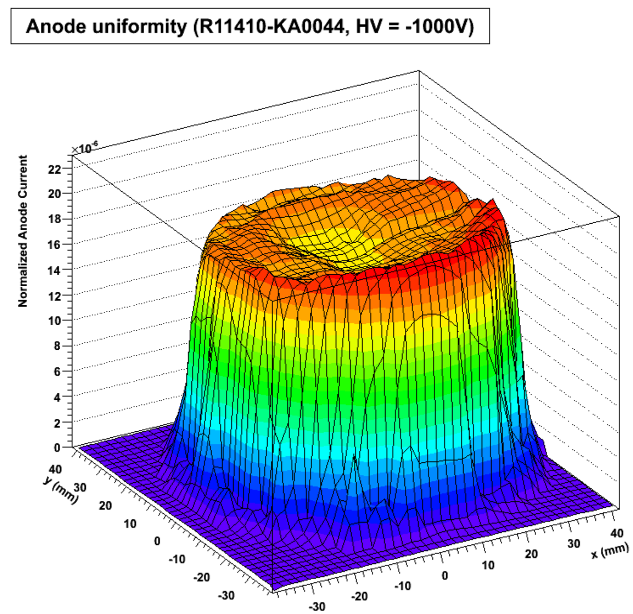


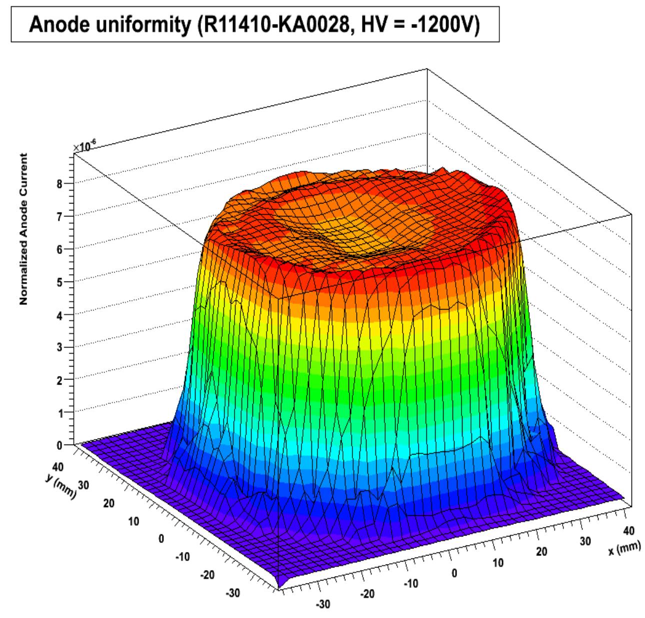


Anode Uniformity (3 inch PMT)



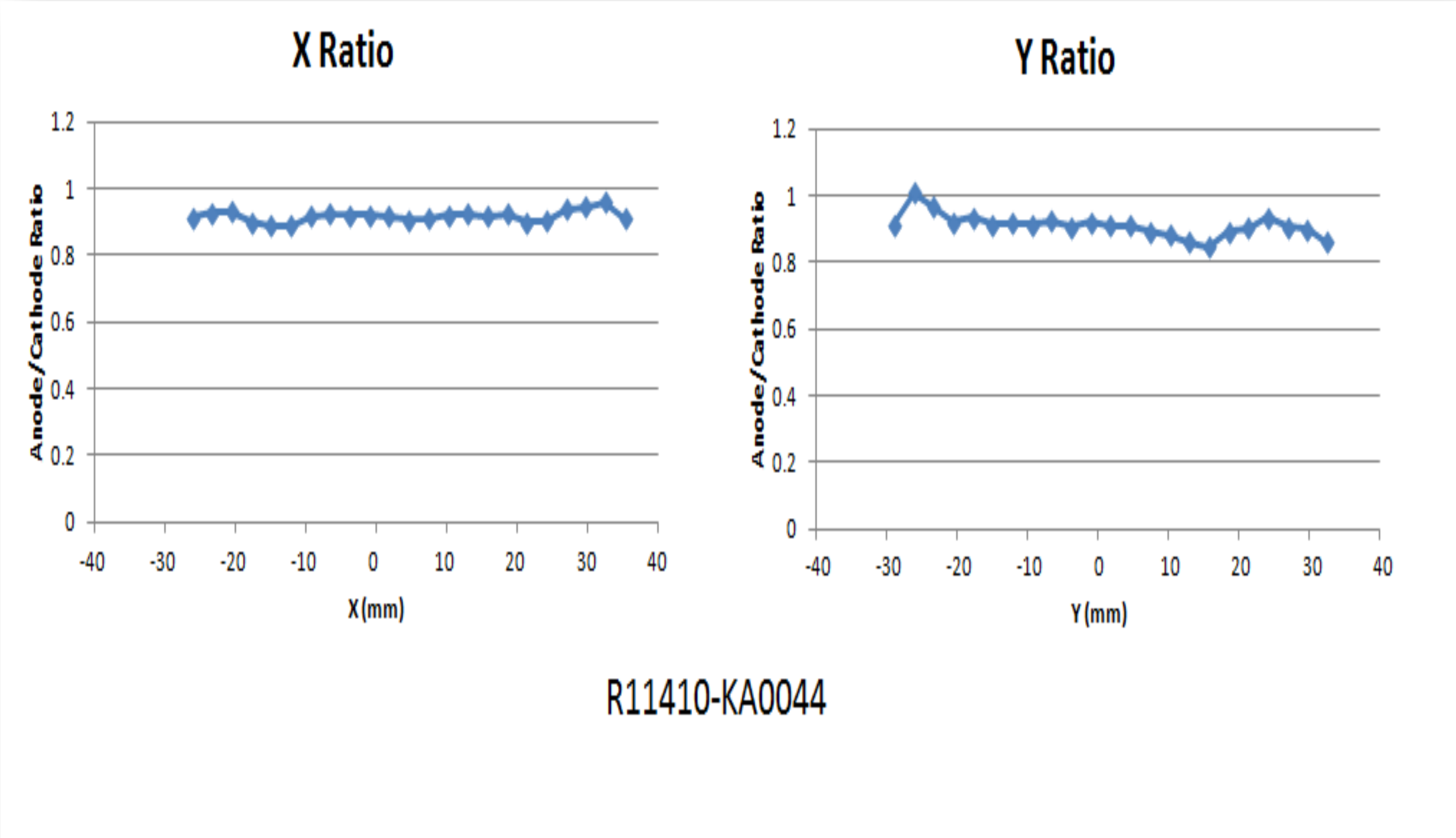






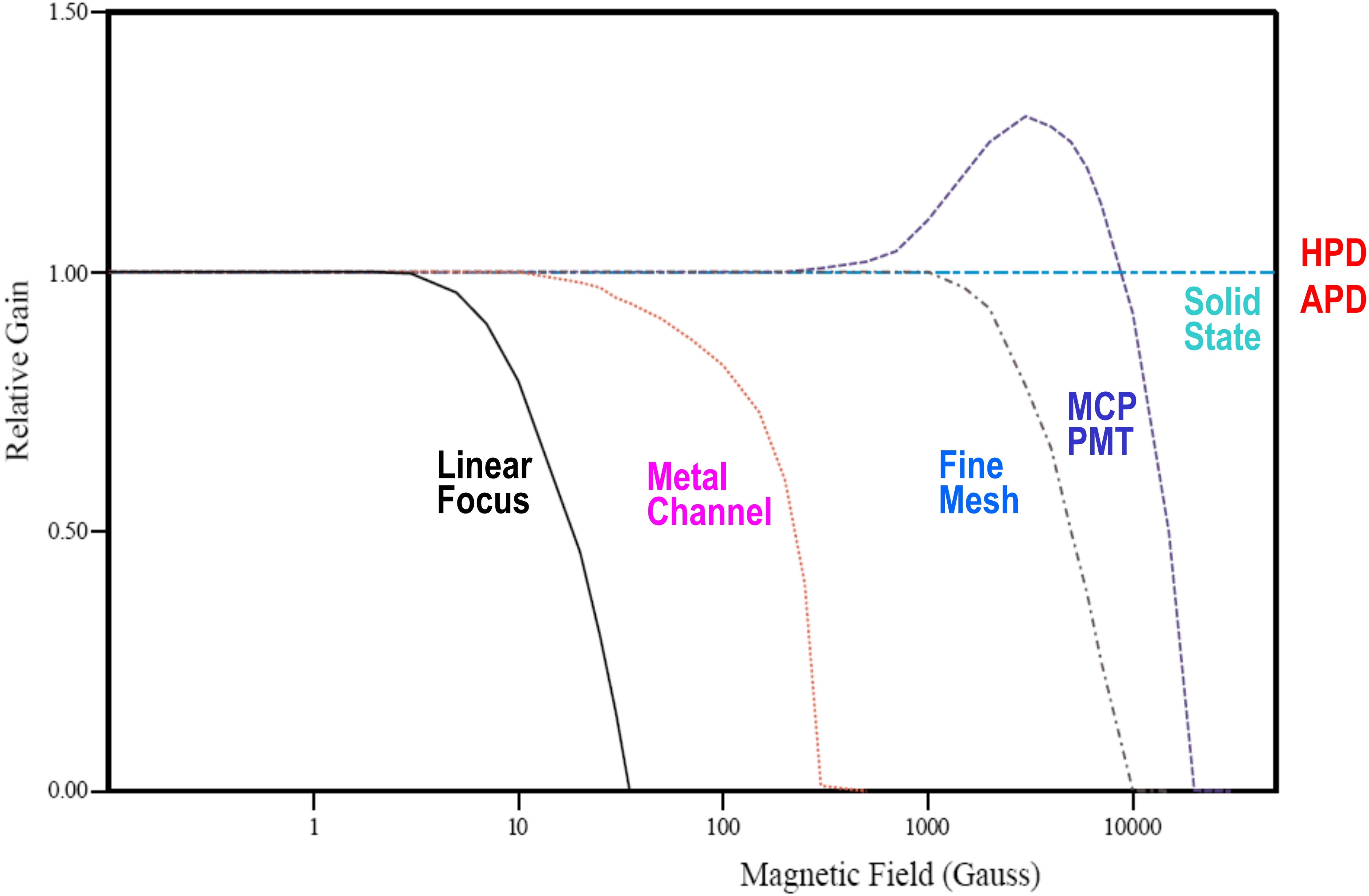
Collection Efficiency (=Anode/Cathode)

(KA0044)

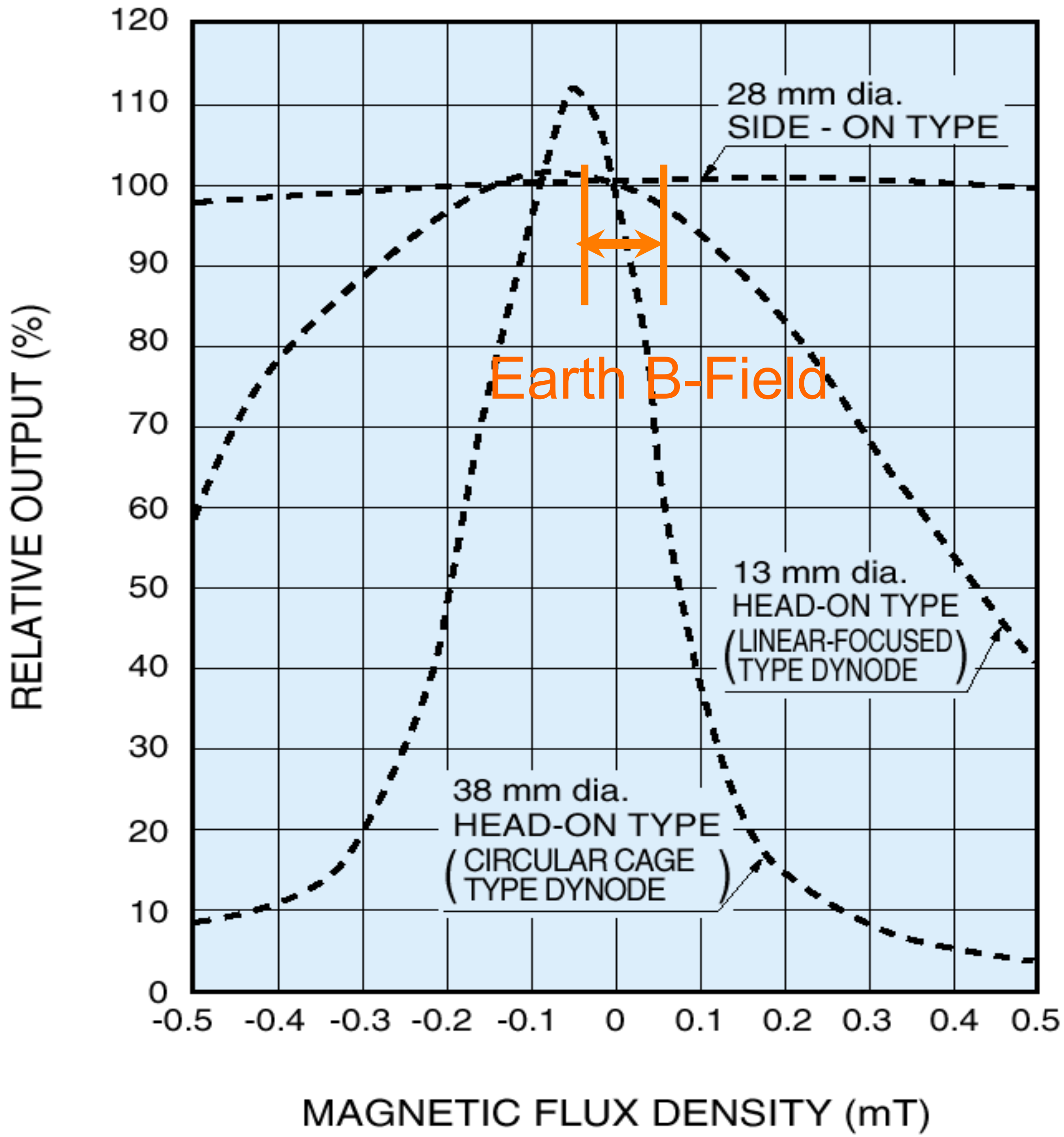


Effect of Magnetic Field

Effect of Magnetic Fields

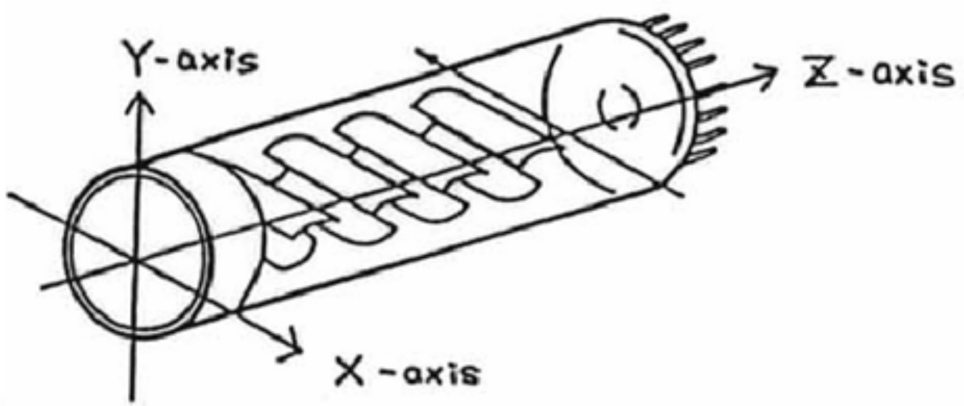


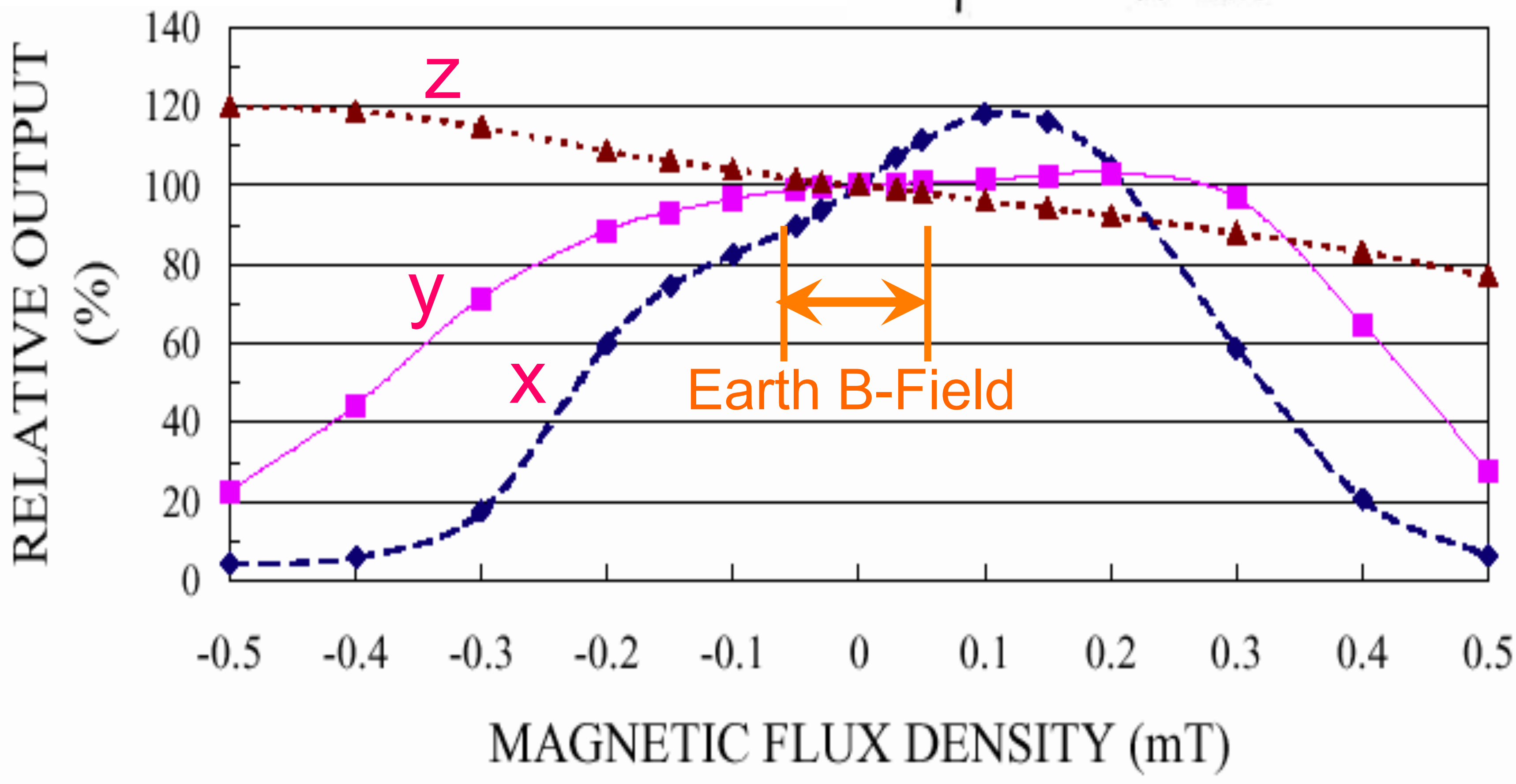
Typical Magnetic Field Effect



Effect of Magnetic Field on Liner-focus 2” PMT

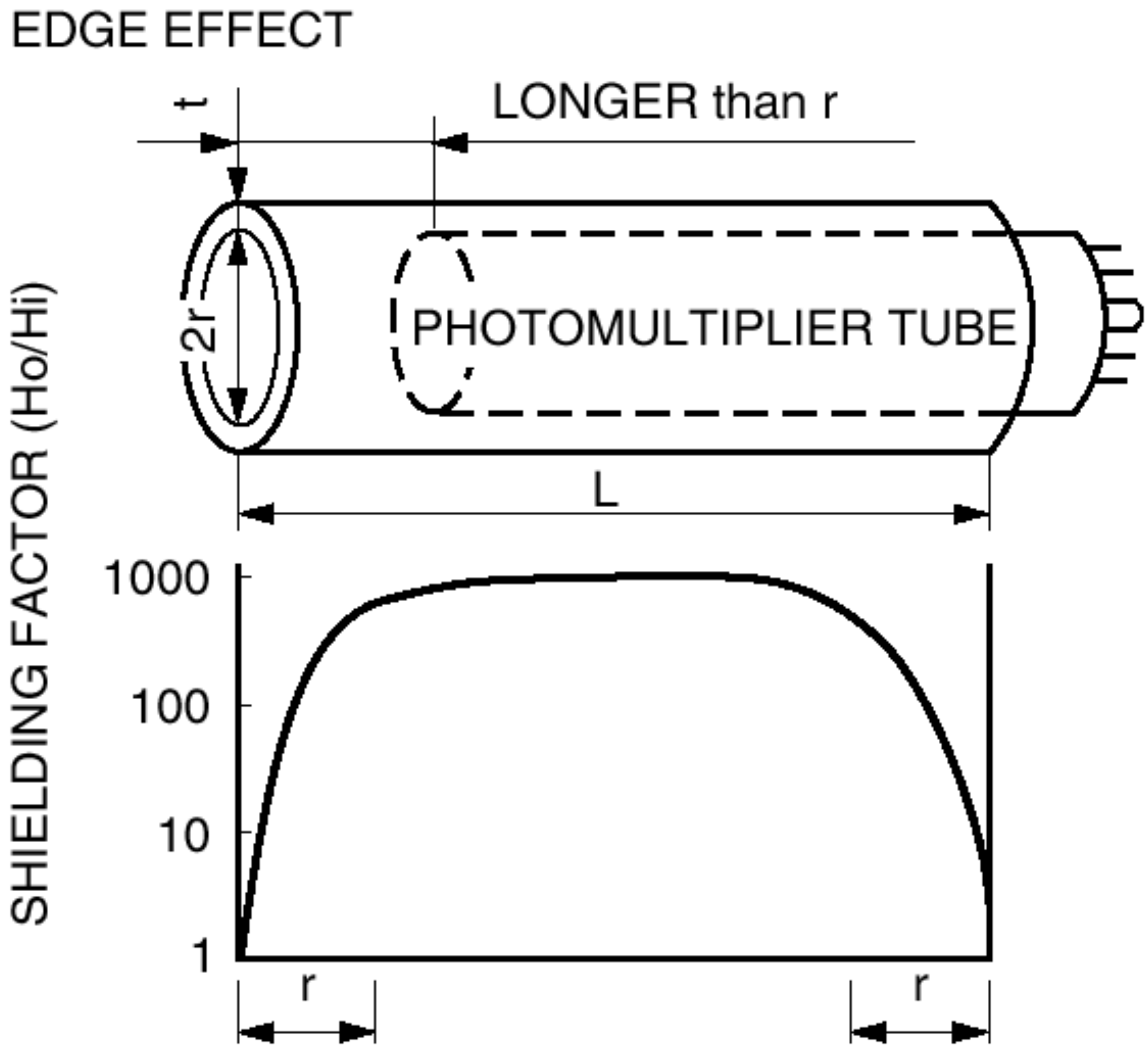
Hamamatsu 2” PMT (R7281-01)





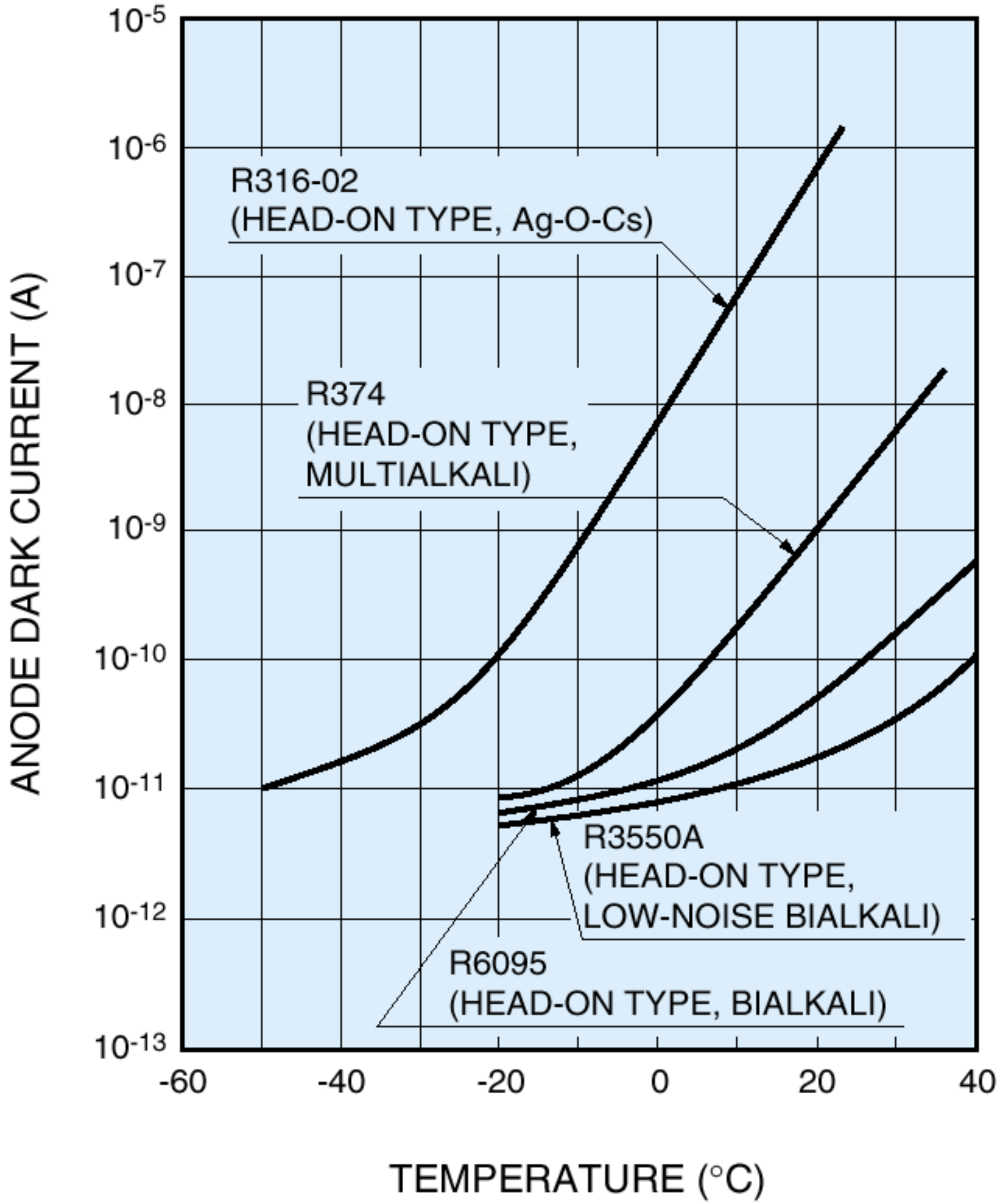
Edge Effect of Magnetic Shields

For effective
shielding,
we need extra
mu-metal
in front.

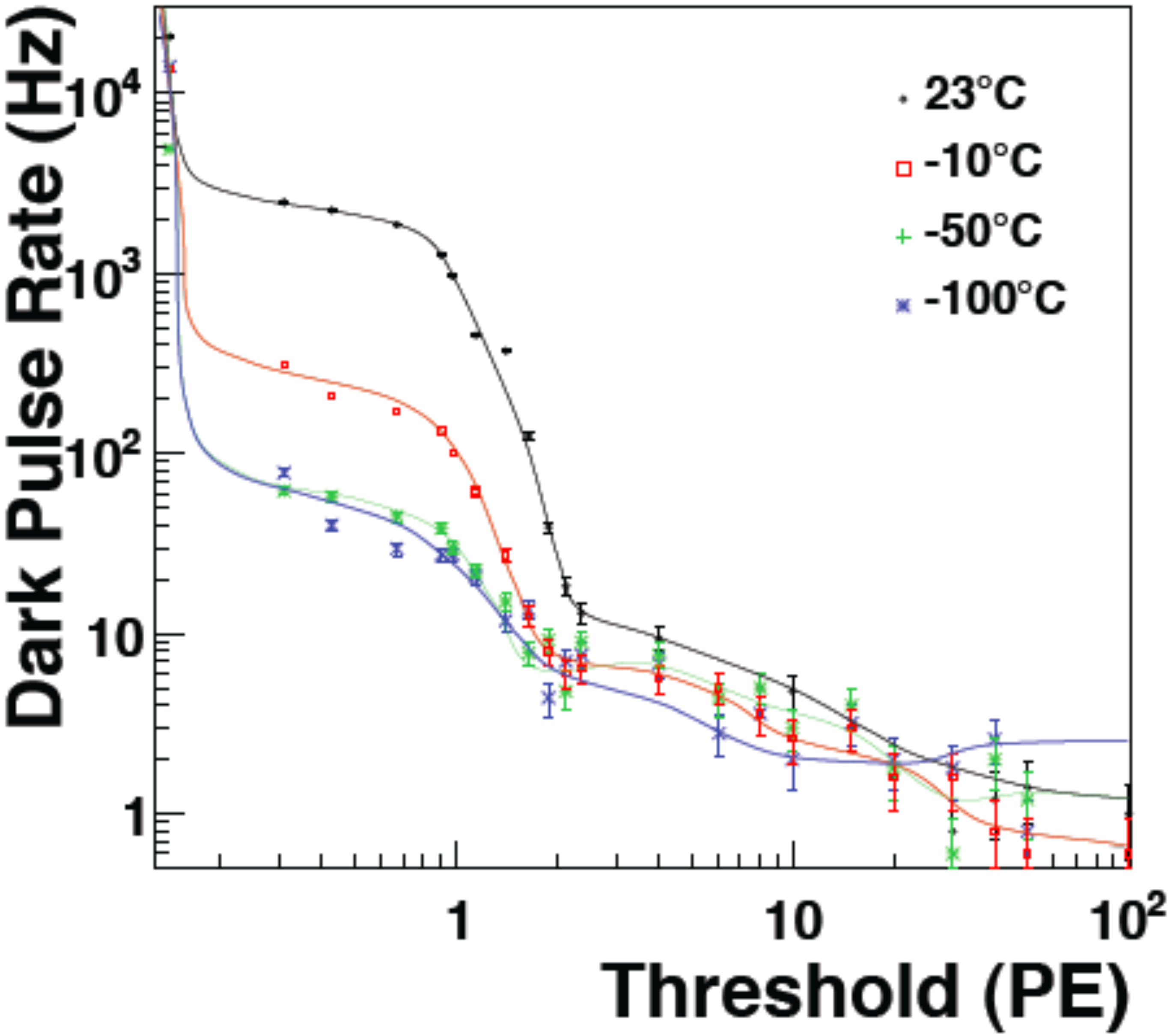


Dark Count

Temperature Dependence of Dark Current

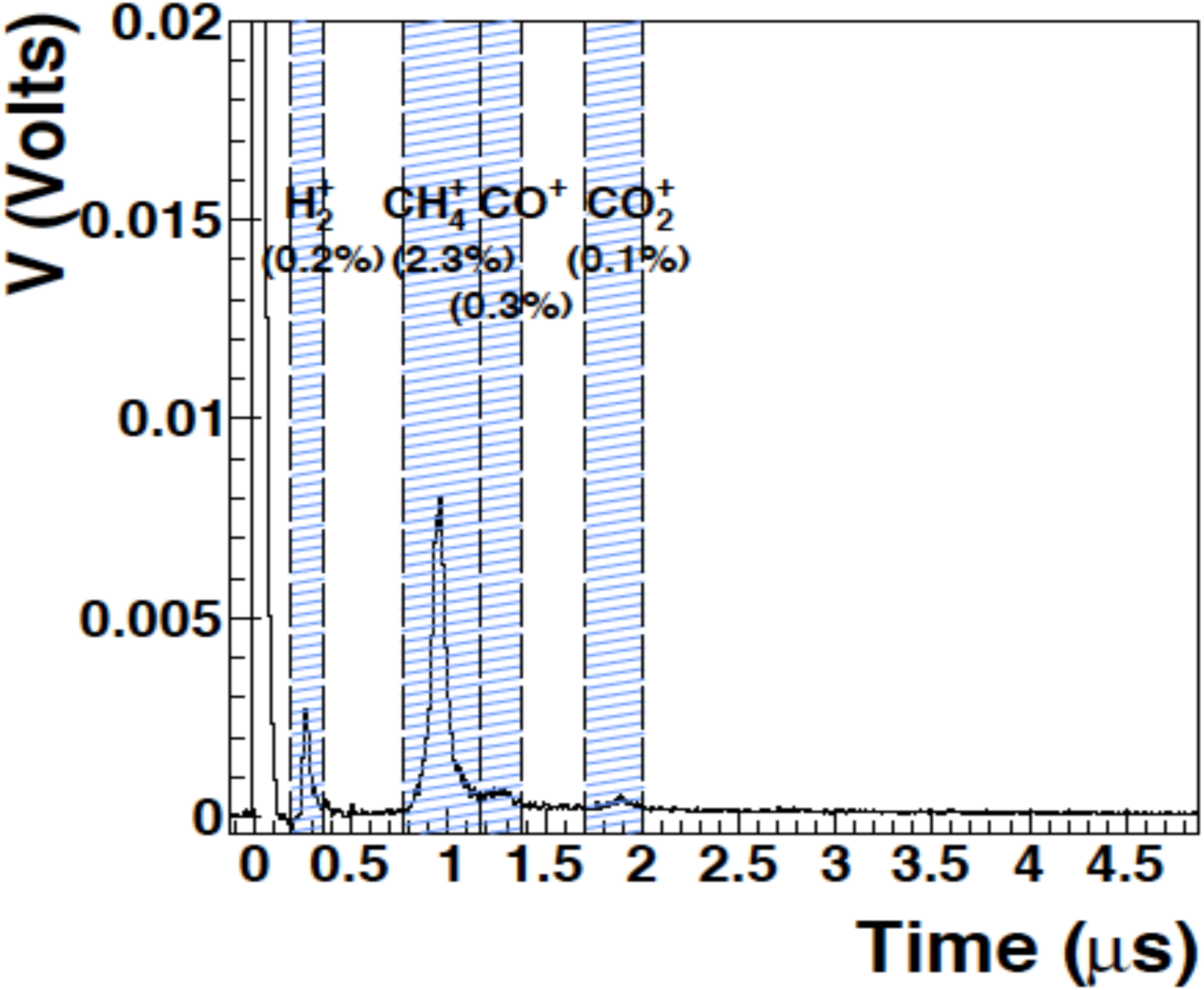


Dark Count Rate vs. Temperature



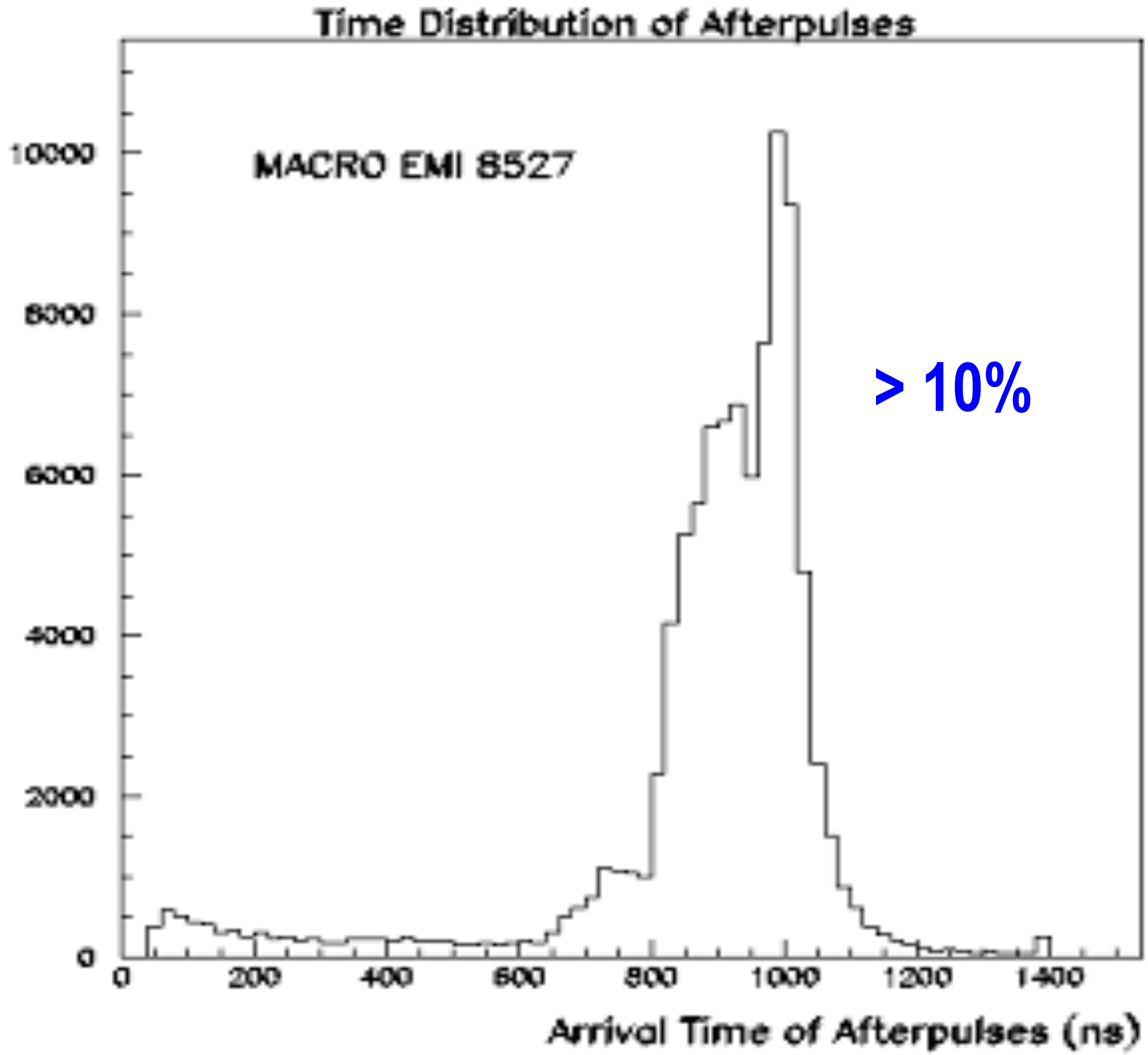
After Pulse

After Pulse (R11410)



After Pulse by Helium

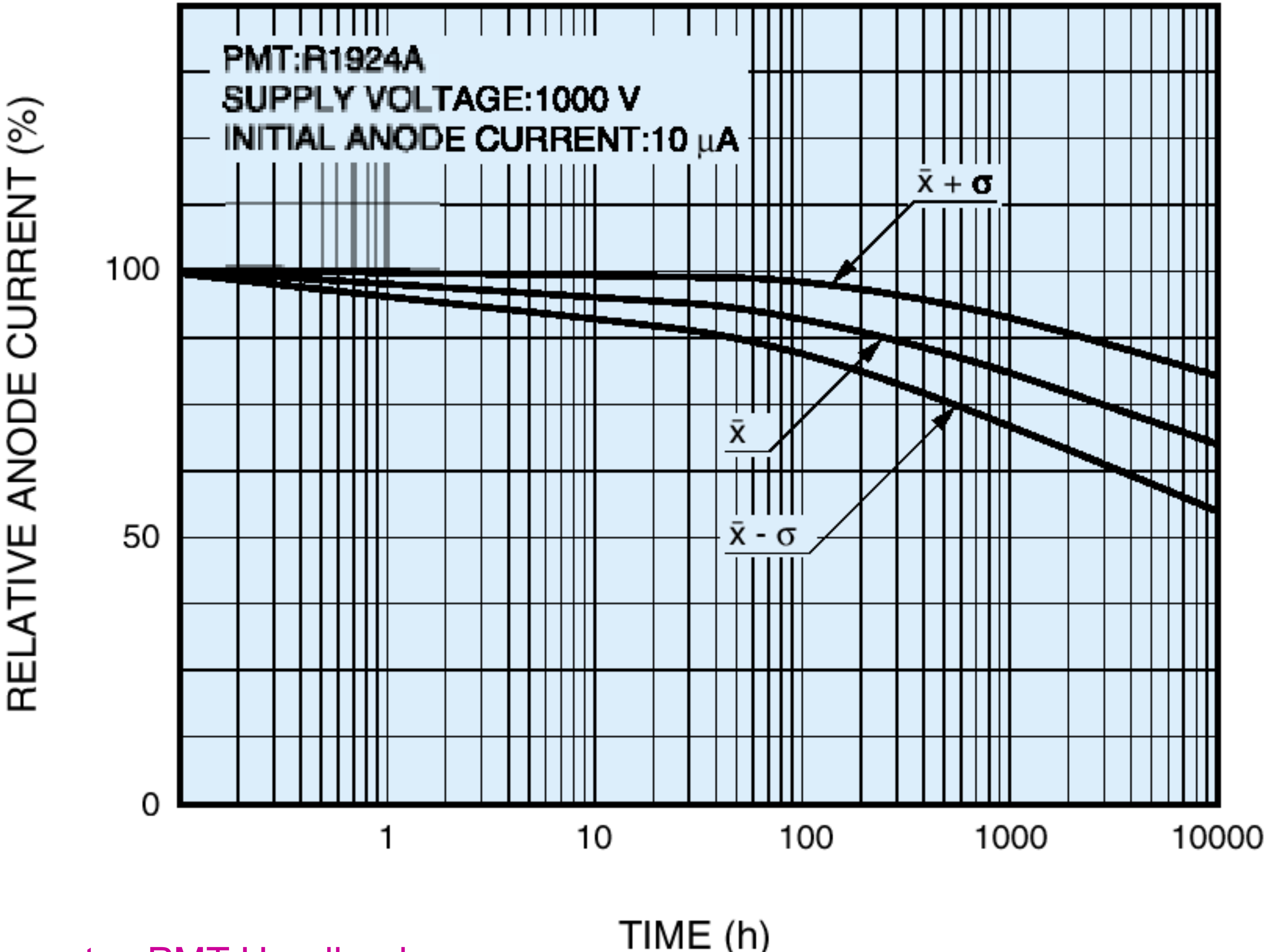
Helium Contaminated PMT from MACRO



> 10%

Long Term Stability

Typical Long-term Stability

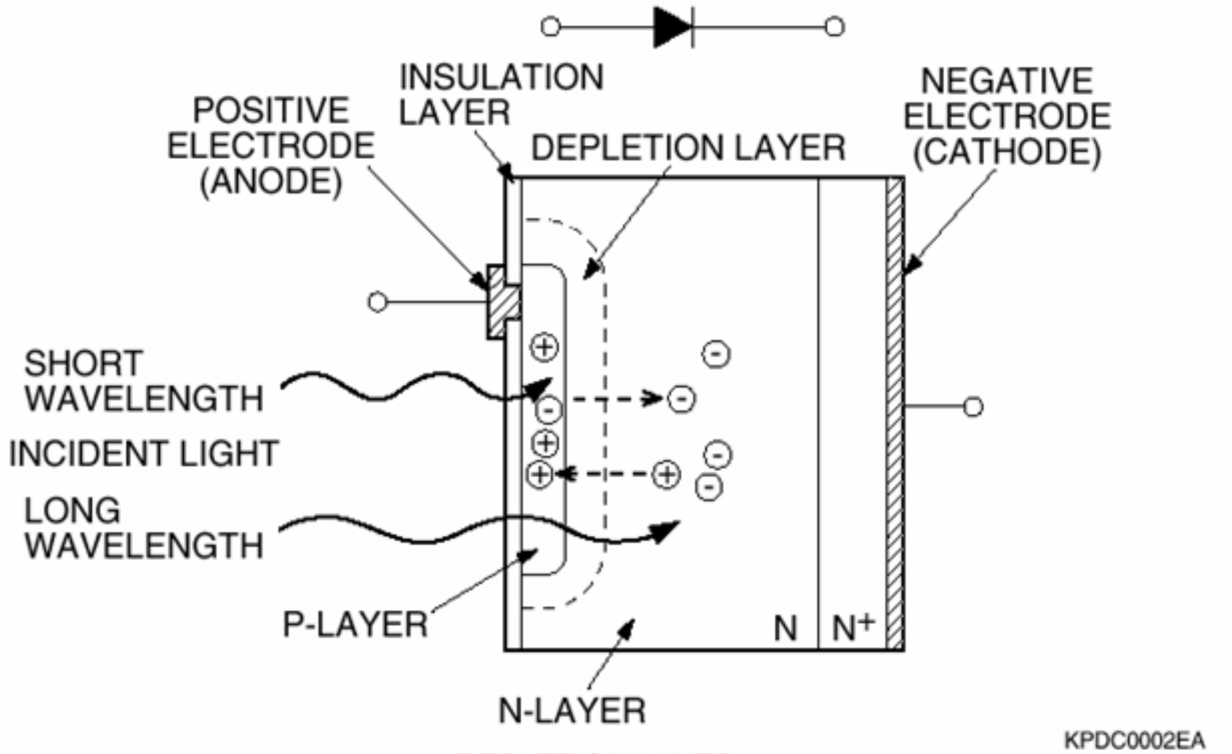


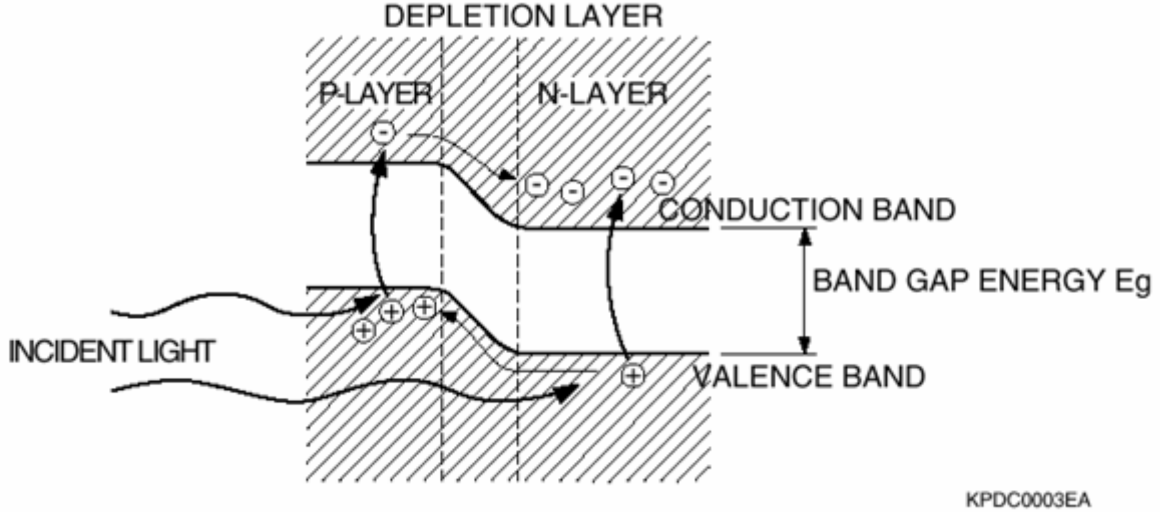
From Hamamatsu PMT Handbook

Other Vacuum Devices

Principle of Silicon Photodiode

- Gain = 1.0
- QE ~ 100%
- Extremely Stable
- Large Dynamic Range



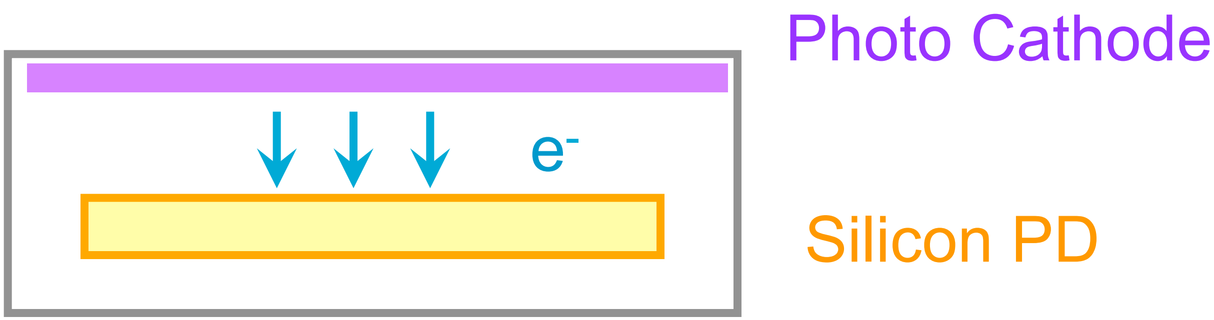


APD (Avalanche Photodiode)

- High Gain (100-1,000), High QE (~70%).
- Then, why not replace PMTs?
- Drawbacks:
  - δ <2, ENF>2 $\Rightarrow$ Effectively QE <35%.
  - Extremely Sensitive to Temperature and Voltage change.
  - Difficult to manufacture uniform, large area.

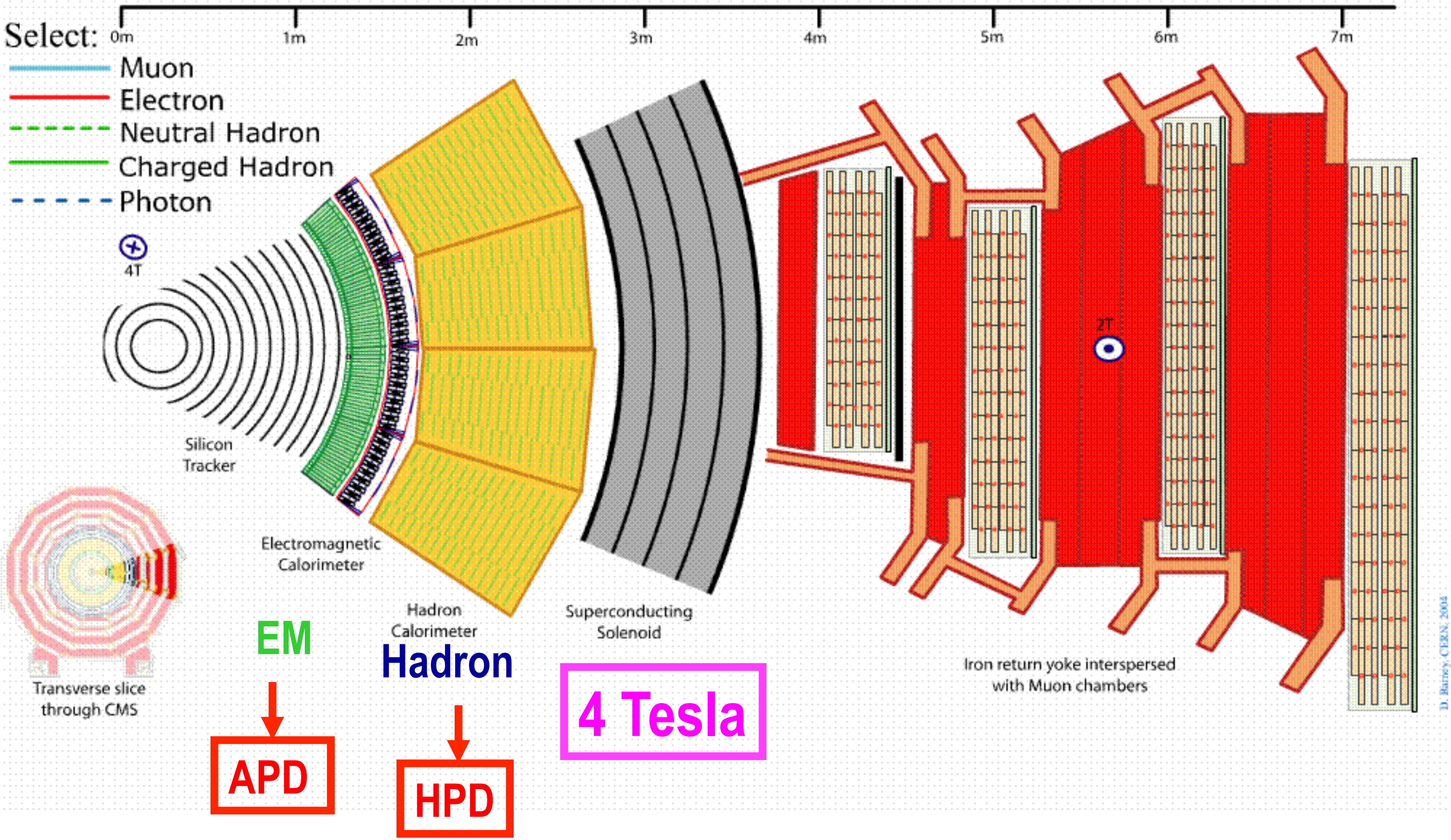
HPD (Hybrid Photodiode)

- In vacuum, Silicon Photodiode instead of dynodes.

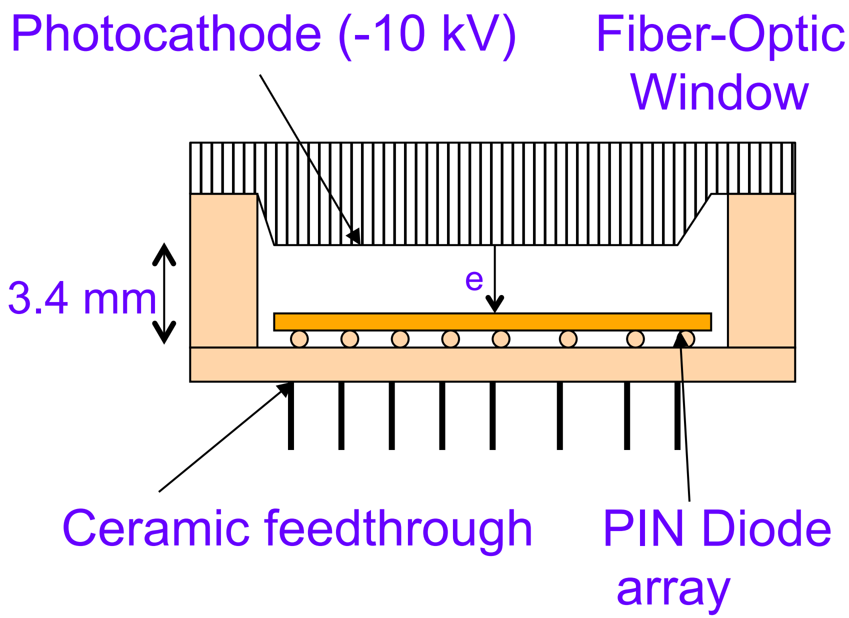


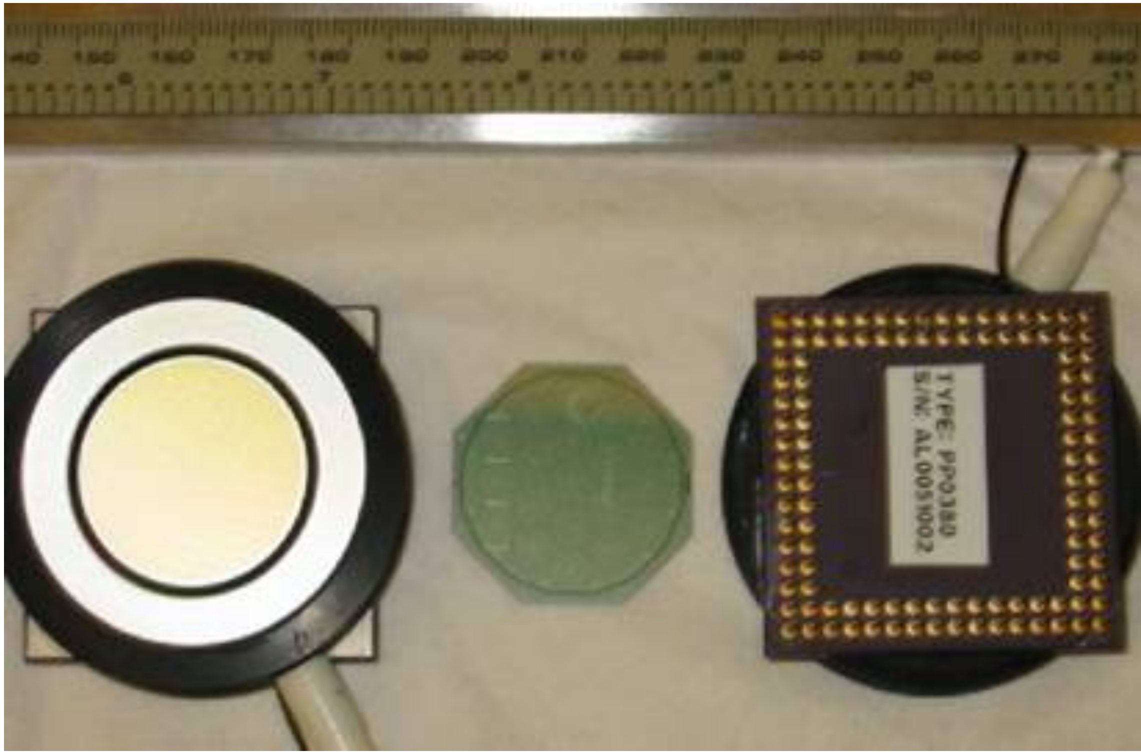
- High Gain (1000-3000), we can count 1-5 photoelectrons.
- Then, why not replace PMTs?

CMS Detector under 4 Tesla



CMS HCAL Multi pixel HPD (DEP)

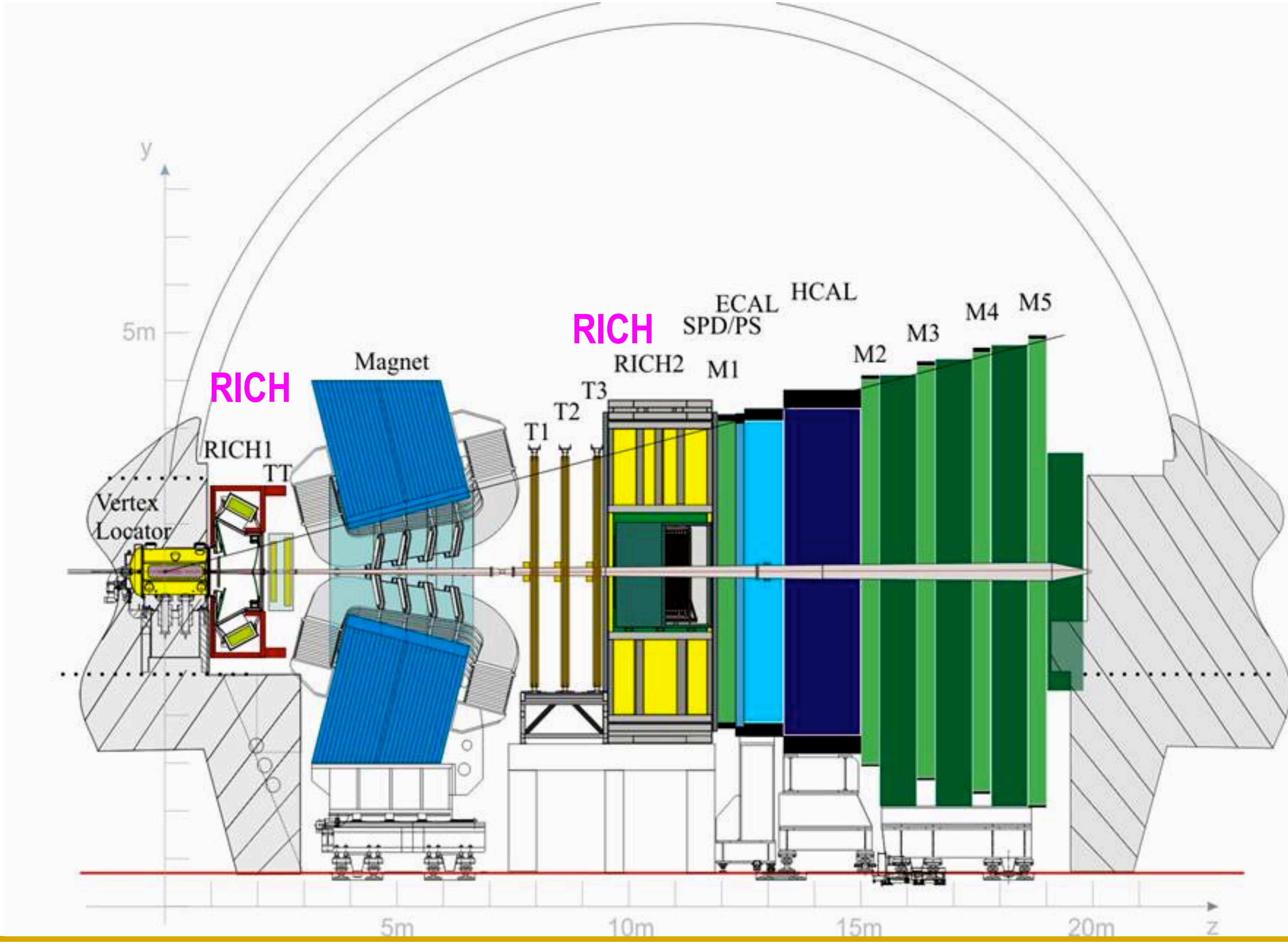




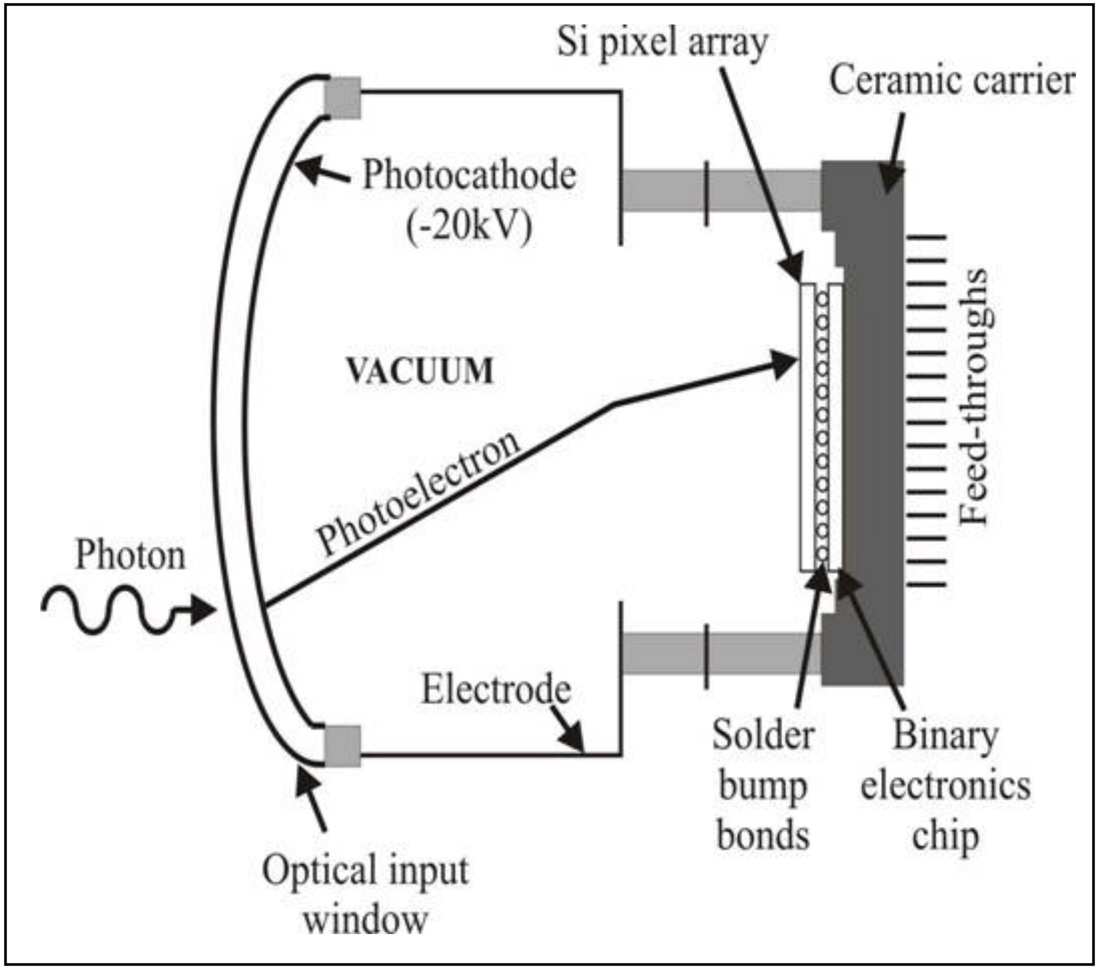
19 channel pixel layout

pixel size: 5.4 mm flat-flat
gap between pixels: 0.04 mm

LHCb experiment



The pixel HPD by DEP (for LHCb)

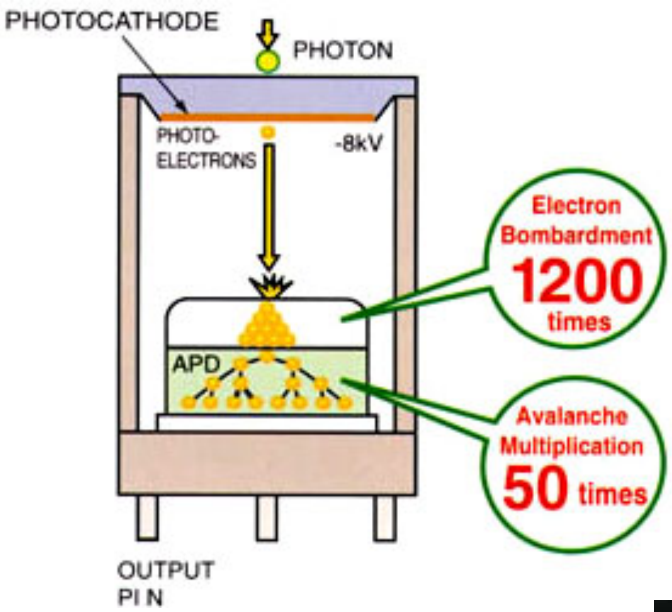


Advantages of this hybrid, pixel structure:

low noise: excellent resolution of single photoelectrons
high channel number/density

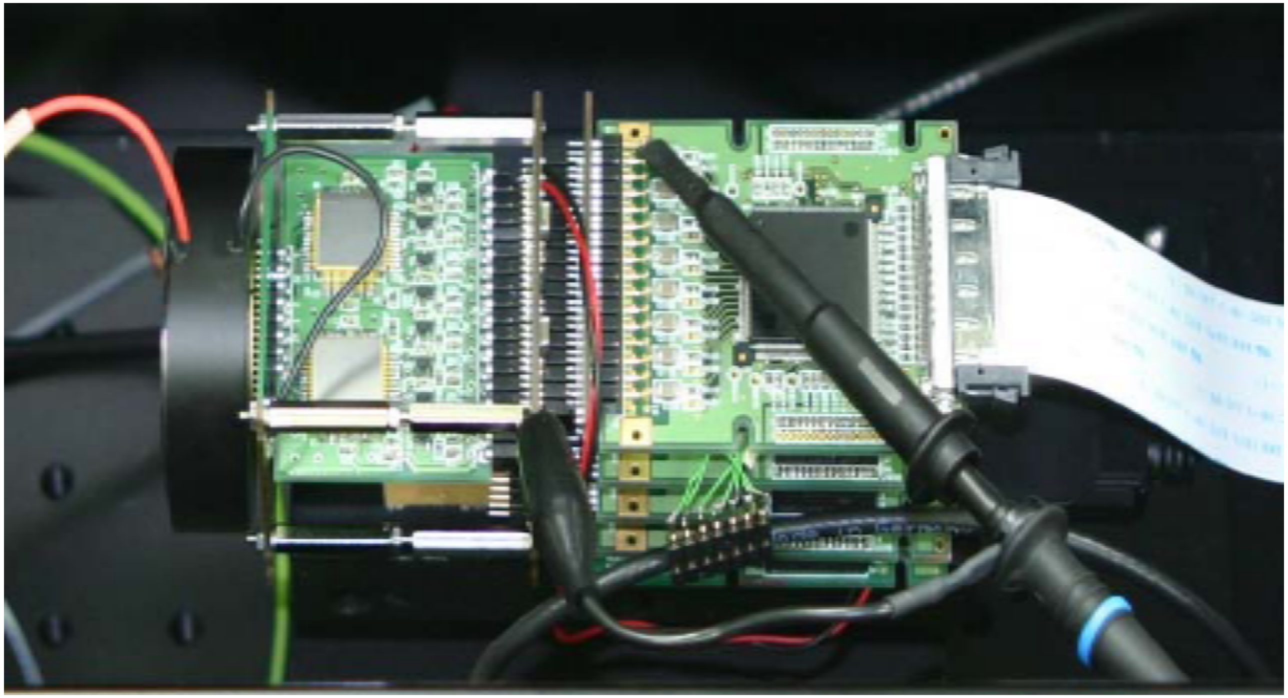
DEP, The Netherlands

Hamamatsu Hybrid APD

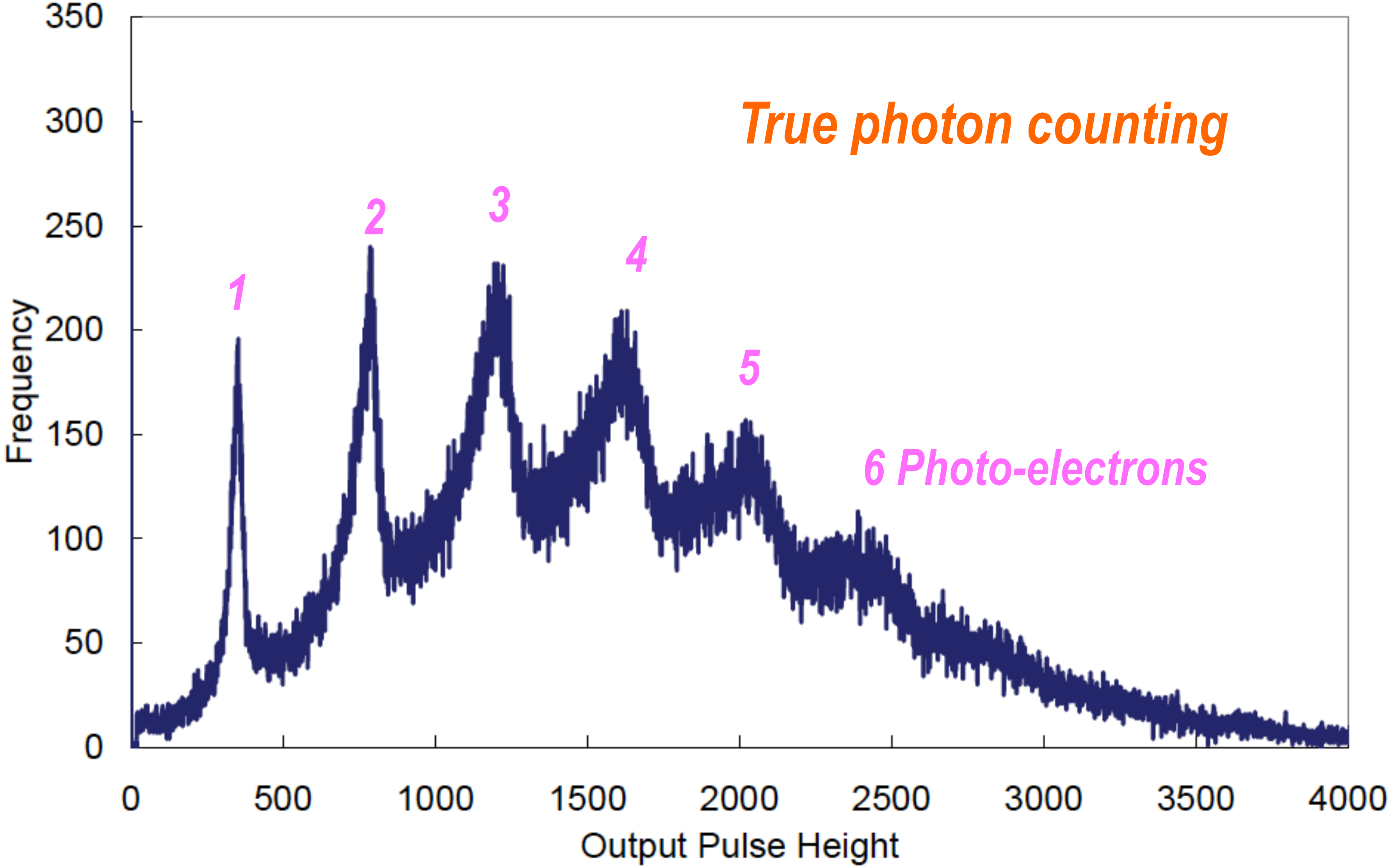


Single Channel HAPD

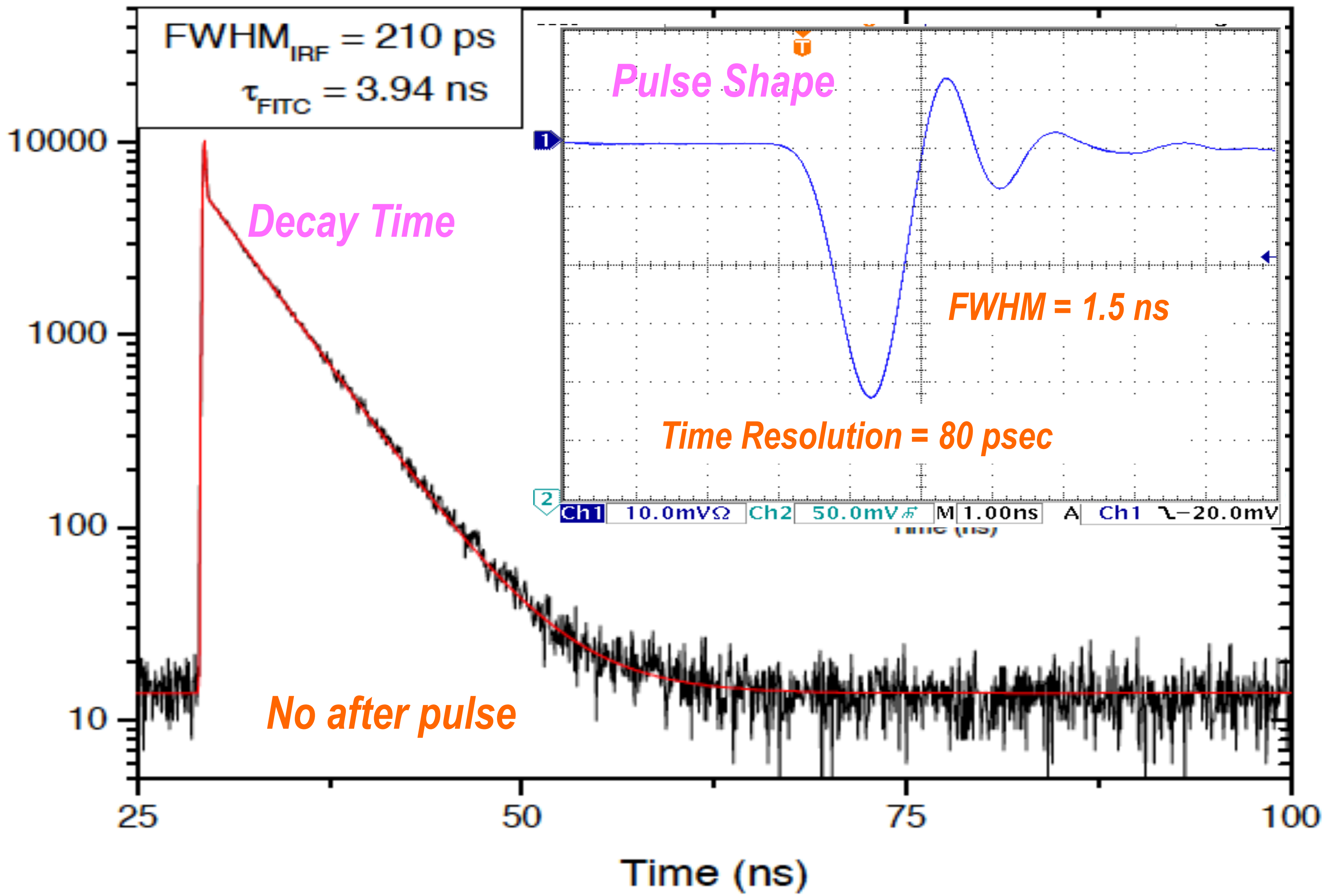
64 Channel HAPD + Readout



1, 2, 3 … Photo-electron Distribution



Decay Time Measurement by HAPD

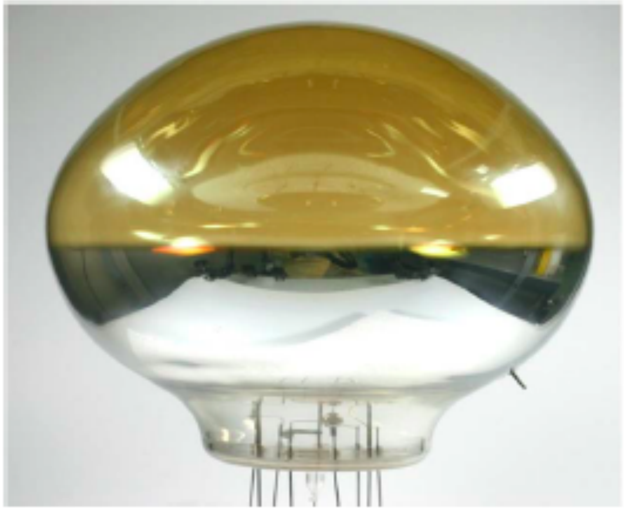


Leica HyD Detector for Confocal Microscope

Hamamatsu Compact HAPD with GaAsP

8 inch HAPD by Hamamatsu

8inch Hybrid Photo-detector, preliminary datasheet

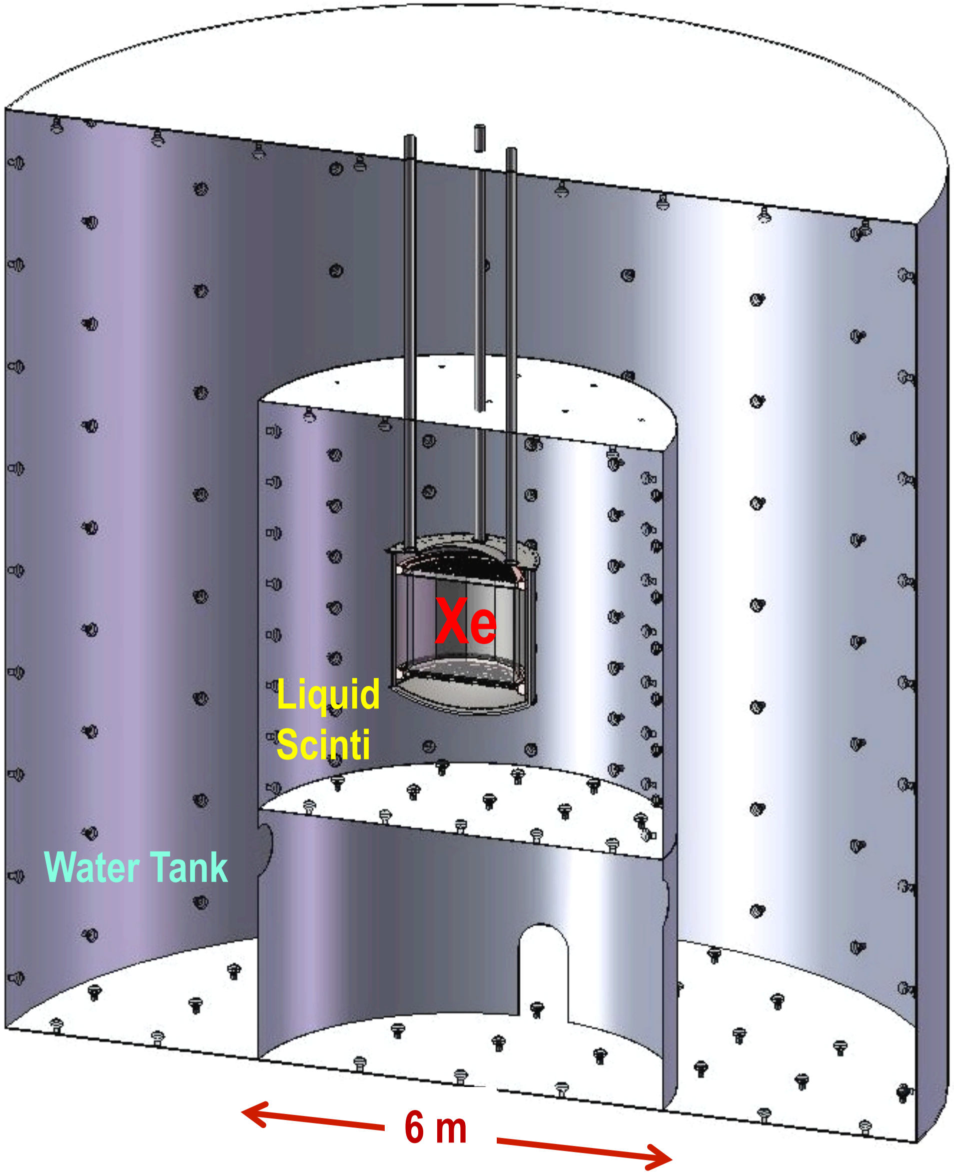


Item		Value/Description	Unit
Spectral Response		300 ~ 650	nm
Photocathode Material		Bialkali	-
Window Material		Borosilicate	-
Secondary Electron Multiplying Method		Semiconductor Electron Bombardment Multiplication	-
Target Semiconductor		5mmφ Avalanche Diode	-
Operating Voltage	Photocathode – Avalanche Diode	8	kV
	Avalanche Diode Bias Voltage	260	V
Total Gain		4×10^4	-
Time Response	Rise Time	1.7	ns
	Fall Time	2.7	ns
	T.T.S. (sigma)	620	ps
Single Photoelectron Pulse Height Resolution (sigma)		20	%

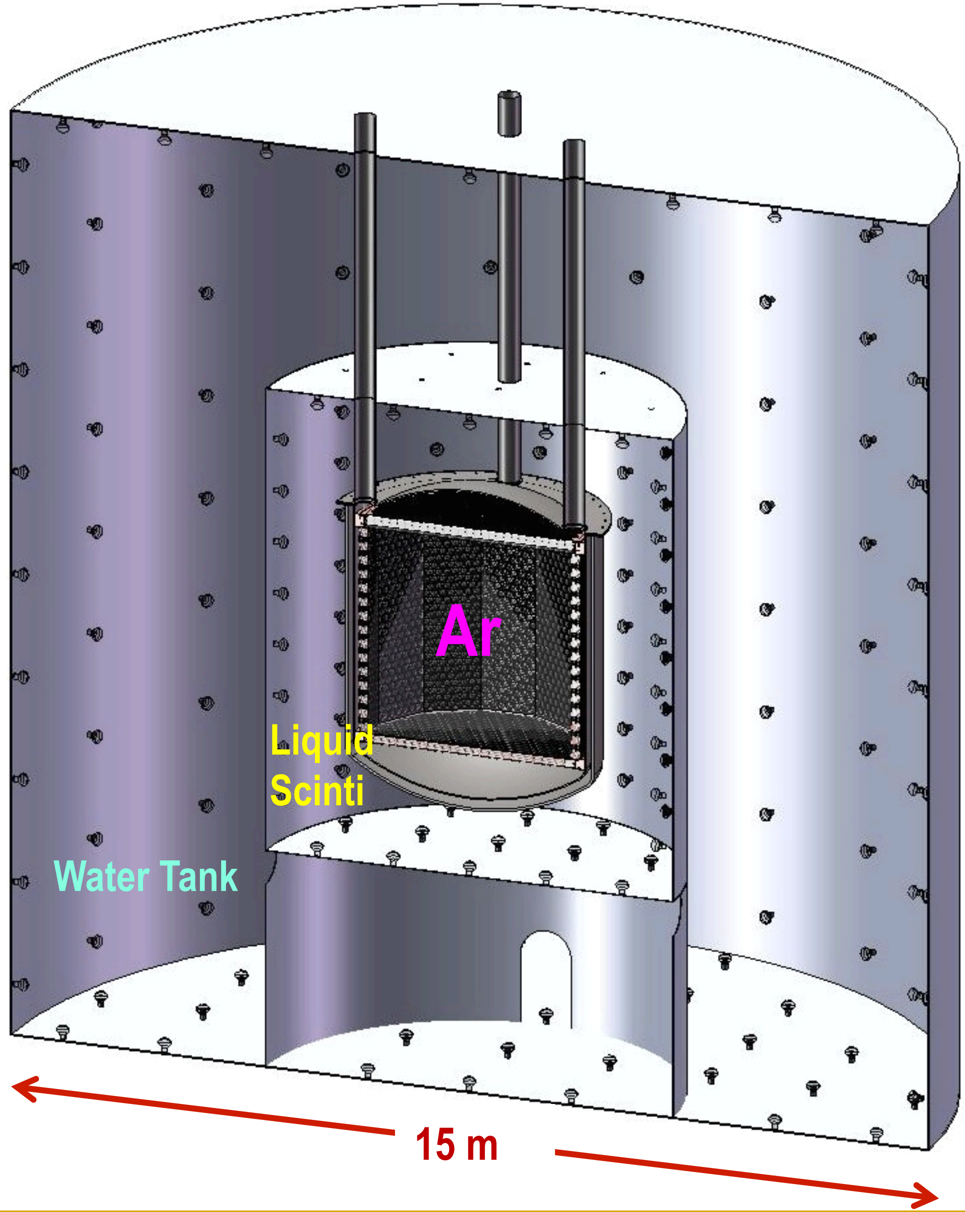
New release at NSS 2012

MAX G3 Dark Matter Detector

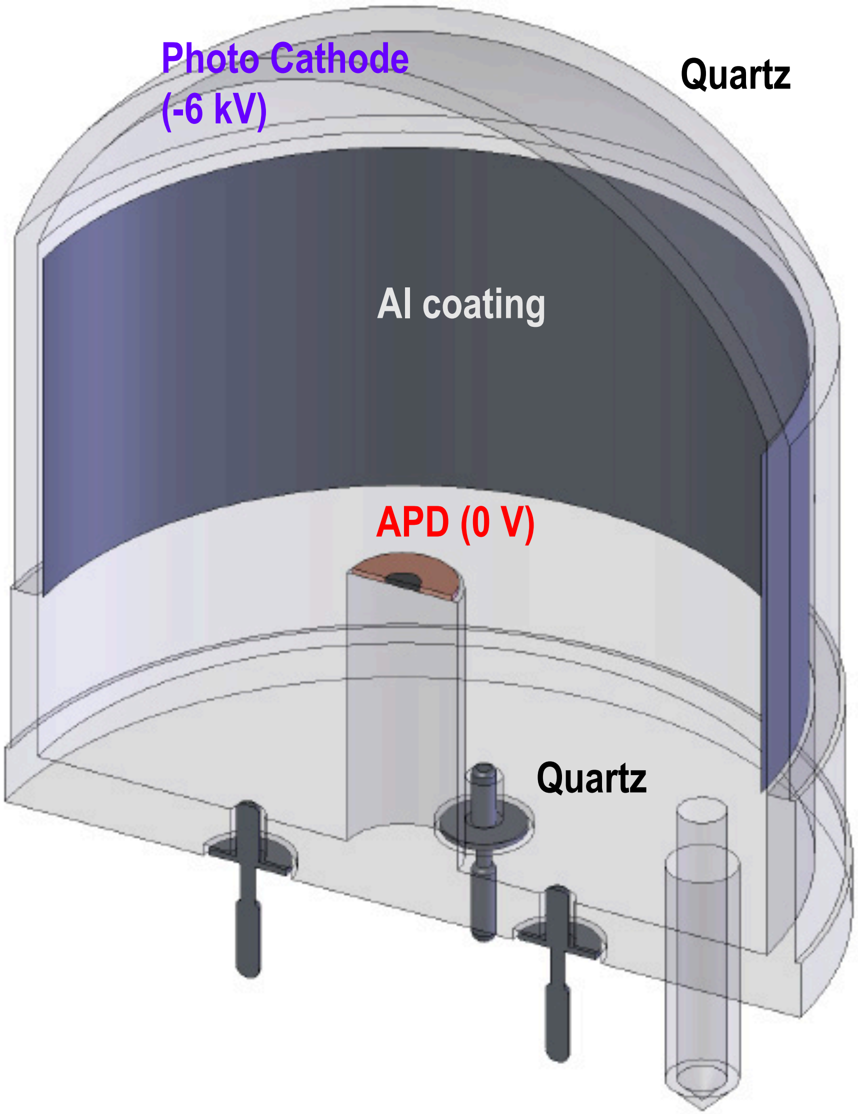
Xe 20 ton (10 ton)

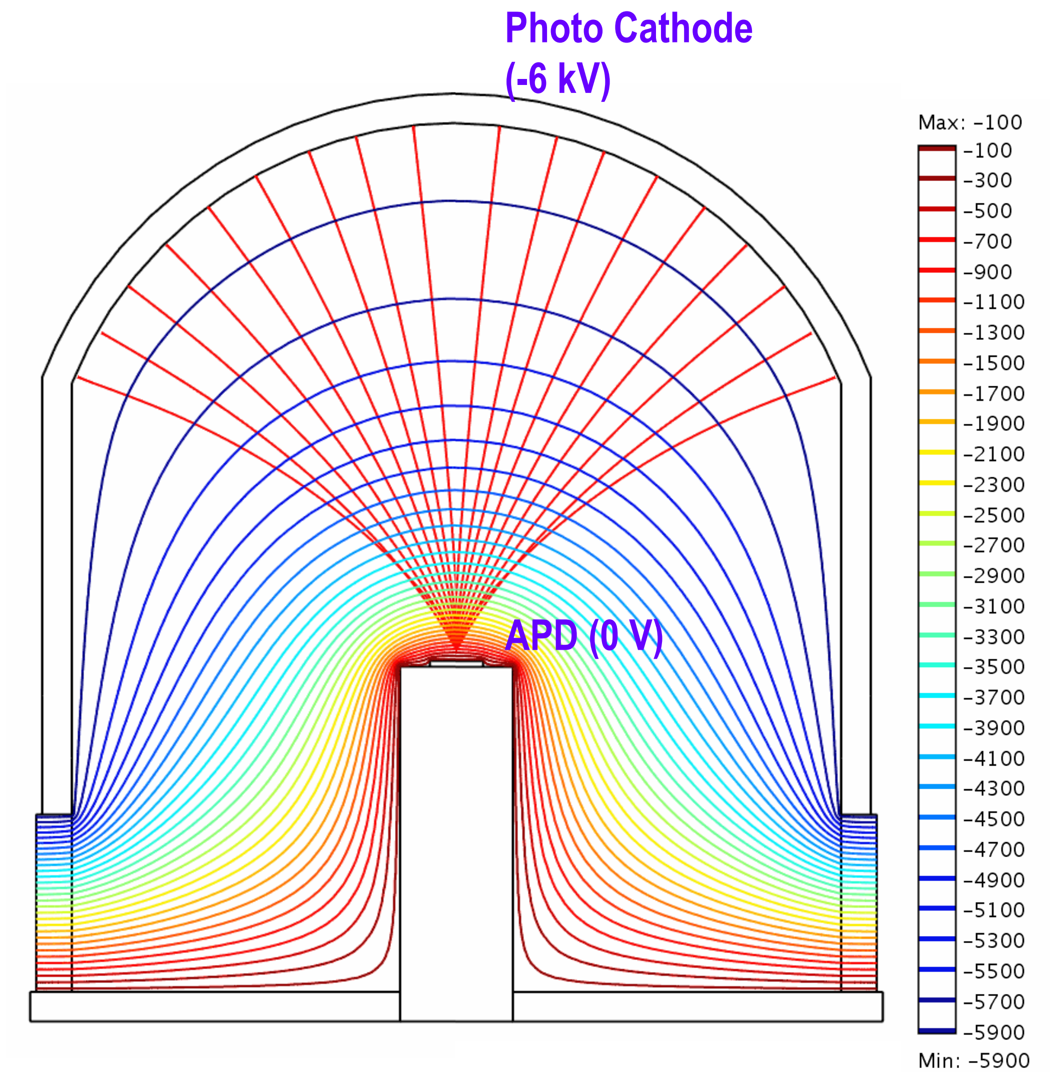


^{40}Ar 70 ton (50 ton)



QUPID (QUartz Photon Intensifying Detector)

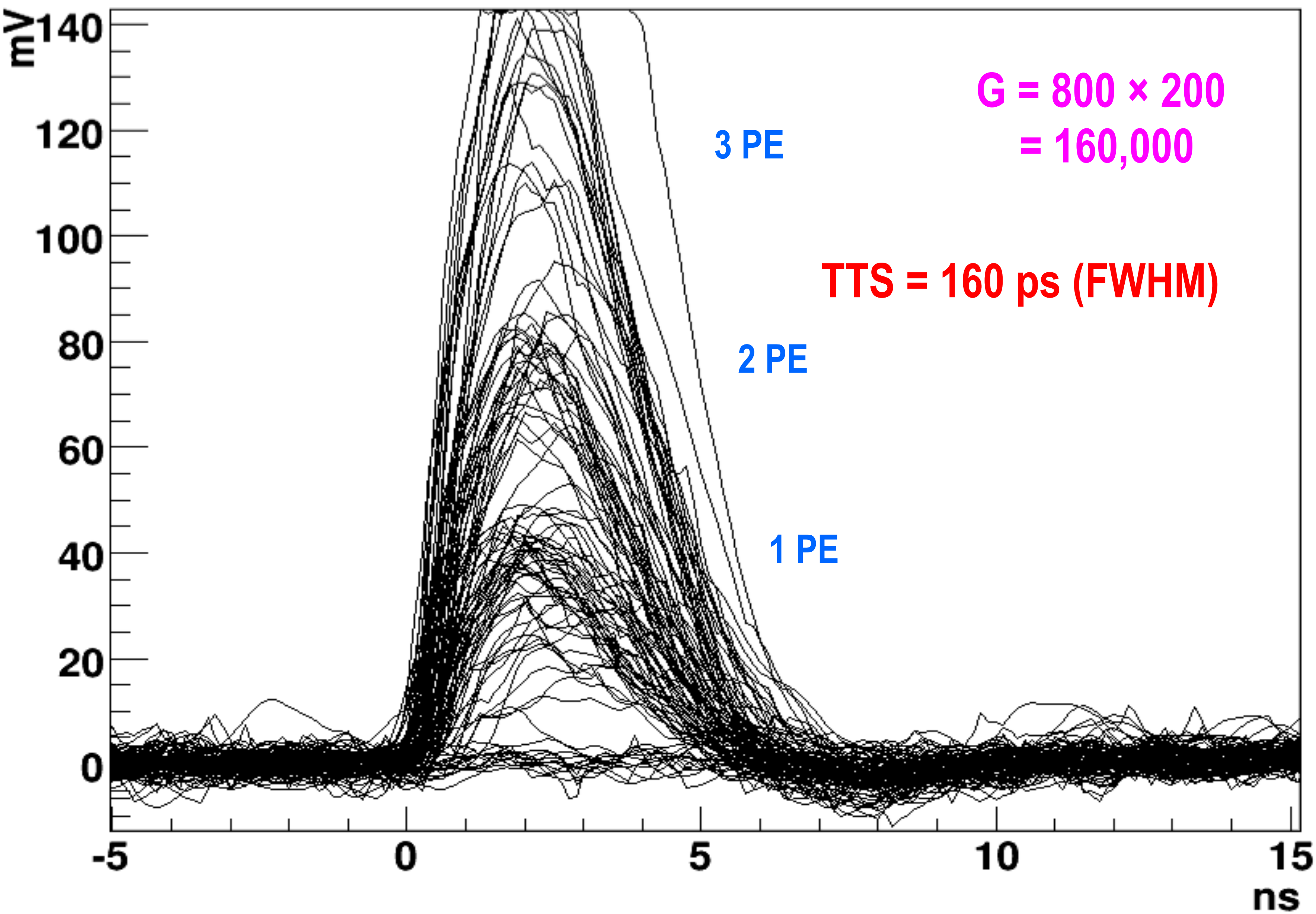




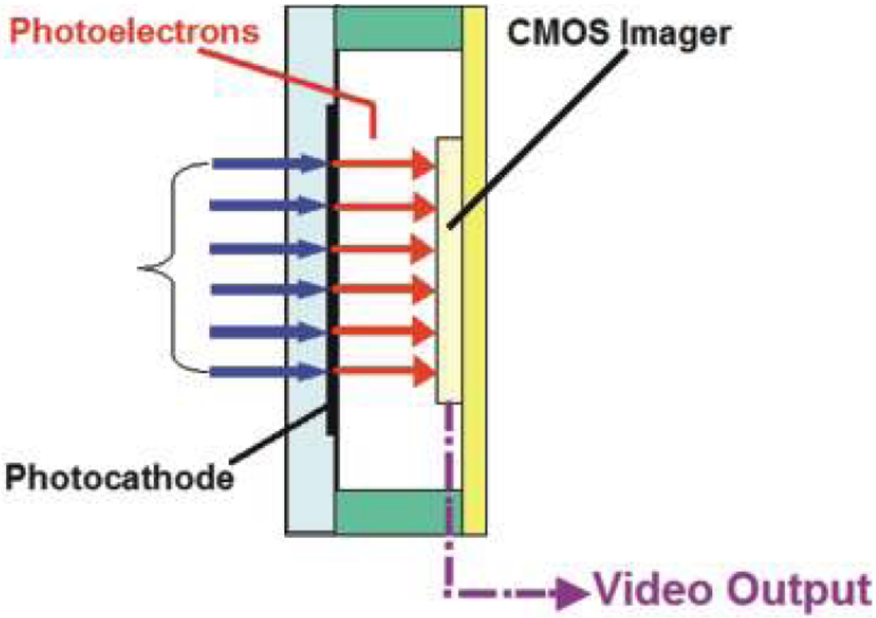
Made by Synthetic Silica only.

Production Version QUPID

1, 2 and 3 PE Distribution with 2m cable



Intevac Electron Bombarded CMOS



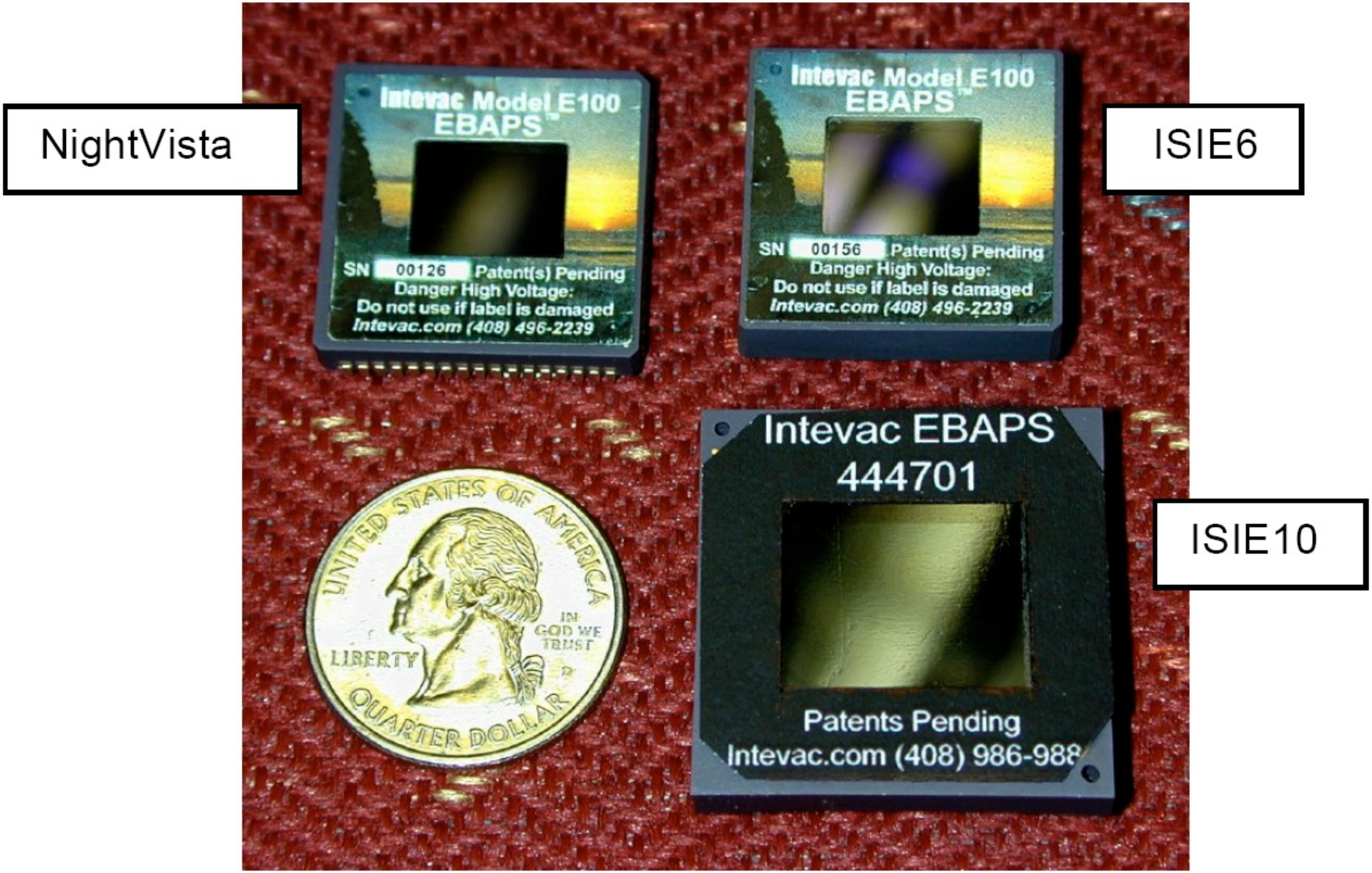
EBAPS® Sensor

Night Vista® Development Kit Contents

- NightVista® Camera
- C-MOUNT Lens
- NightVista® User Manual on CD
- Set of all required cables
- Application software
- Power cord
- Transit case

Signal Format	RS-170
Imaging Device	1/2"
Spectral Response Range	400 – 900 nm
Minimum Faceplate Illumination	10-5 Lux
Output Resolution	VGA (640 x 480) at 30 fps
Power Requirement	5 VDC
Power Consumption	< 1.8 W (nominal)
Dimensions (W x H x D)	1.9" x 1.9" x 2.6" (see schematic, below)
Weight	4.5 ounces
Communication	RS-232
Lens Mount	C-mount
Storage Temperature	-65°C to +70°C
Operating Temperature	-10°C to +40°C
Relative Humidity	0 – 90% Non-condensing
Camera Functions	Non-uniformity Correction Programmable Gamma / Contrast Curve Histogram Equalization Edge Enhancement Time Stamp Digital Zoom (2:1) Image Orientation Digital Watermark Freeze Frame Capture
Shipped Accessories	Operator's Manual Control Software 120 VAC Power Supply
Available Options	USB 2.0 Video Bus (Video & Control) 9 VDC Power Requirement 2.8 W (nominal) Power Consumption

EBAPS by Intevac



Energy Resolution

Anode Signal (E)

- **Definition:**

$$E = N_\gamma \cdot QE \cdot CE \cdot \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$$

$$= N_\gamma \cdot QE \cdot G_I = N_{pe} \cdot G_I$$

(by Industries)

$$= N_\gamma \cdot QE \cdot C_{ol} \cdot G_p$$

$$= N_\gamma \cdot DQE \cdot G_p$$

(by Physicists)

(N_γ = No. of Incident Photons)

(N_{pe} = No. of Photo-electrons)

Energy Resolution (σ/E)

- In ideal case:

$$\frac{\sigma}{E} = \frac{\sqrt{N_\gamma}}{N_\gamma} = \sqrt{\frac{1}{N_\gamma}}$$

- In reality:

$$\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_\gamma \cdot QE \cdot CE} + \left(\frac{ENC}{N_\gamma \cdot QE \cdot CE \cdot G} \right)^2}$$

- – N_γ Number of incident photons
- – QE Quantum Efficiency
- – CE Collection Efficiency:
- – ENF Excess Noise Factor (from Dynodes)
- – ENC Equivalent Noise Charge (Readout Noise)
- – G Gain

Excess Noise Factor (ENF)

- **Definition:**

$$ENF \equiv \frac{\sigma^2_{Output}}{\sigma^2_{Input}}$$

- **In case of PMT:**

$$ENF = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n}$$

- **How to measure:**
  - Set N_{pe} = 10-20 (for nice Gaussian).
  - Measure σ/E of the Gaussian distribution.
  - ENF is given by

$$ENF = (\sigma/E)^2 (N_{pe} \cdot CE)$$

Single PE Distribution

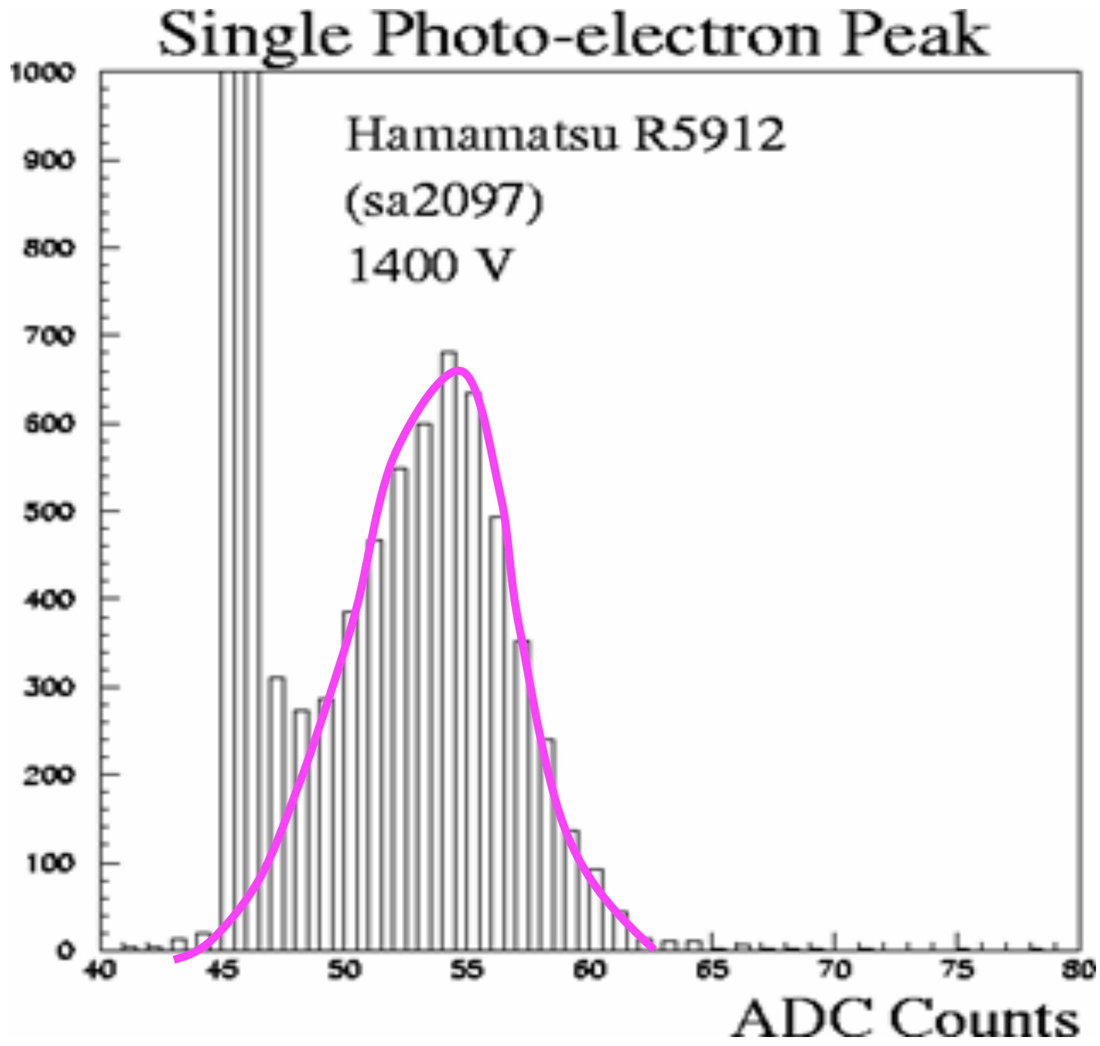
- σ of the single PE distribution is given by

$$\left(\frac{\sigma}{E}\right)_{Single\_PE} = \sqrt{\frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n}} = \sqrt{ENF - 1}$$

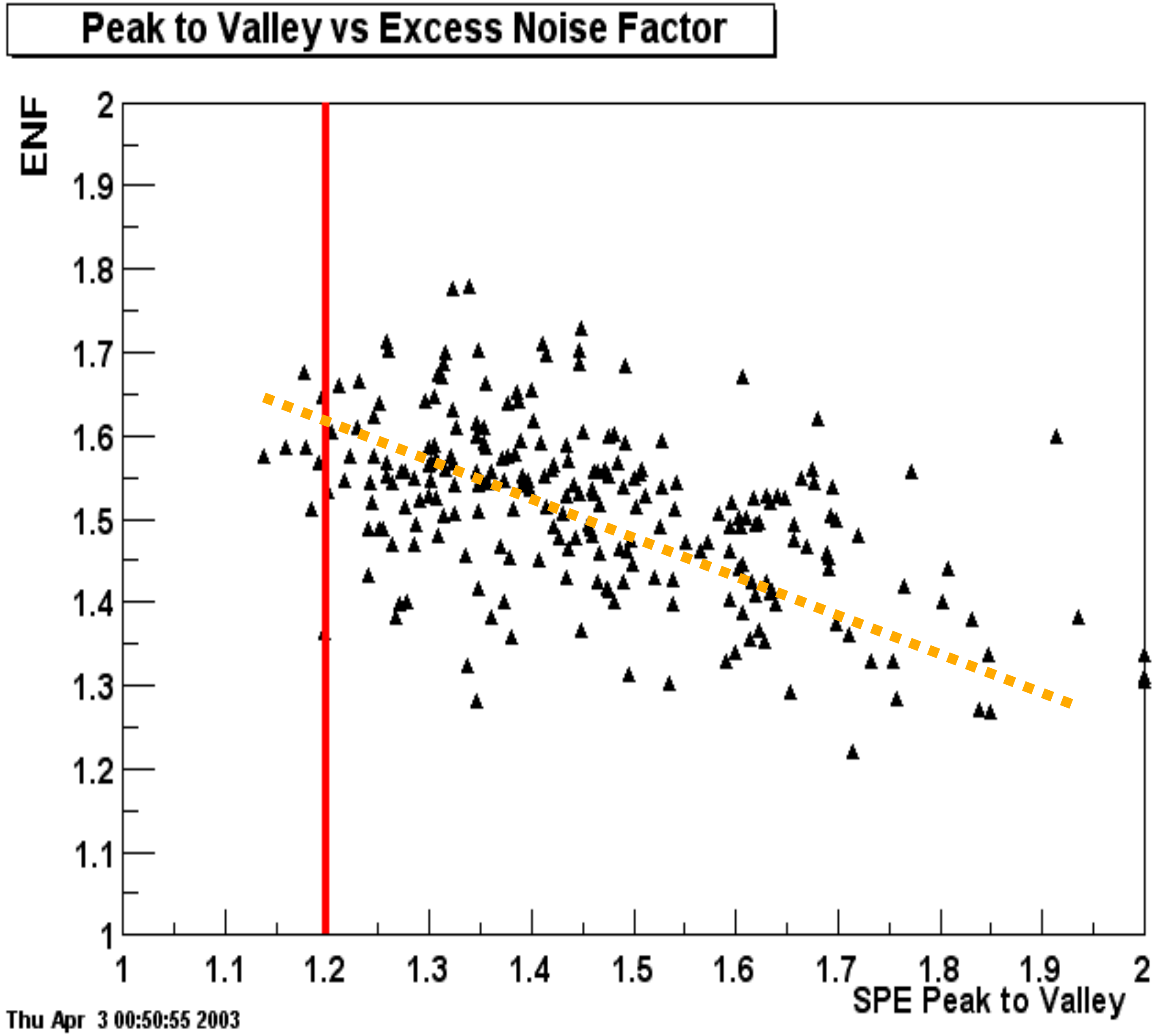
- Thus ENF is related to Peak to Valley Ratio.

Single PE Distribution

- To see single PE, tune light intensity so that >90% gives pedestal.
- If δ_1 >>5, ENF<1.4, Clear single PE can be seen.
- The true position is given by the "Center of Mass" including signal below the pedestal.



ENF vs. P/V Ratio of 270 Auger-SD PMTs

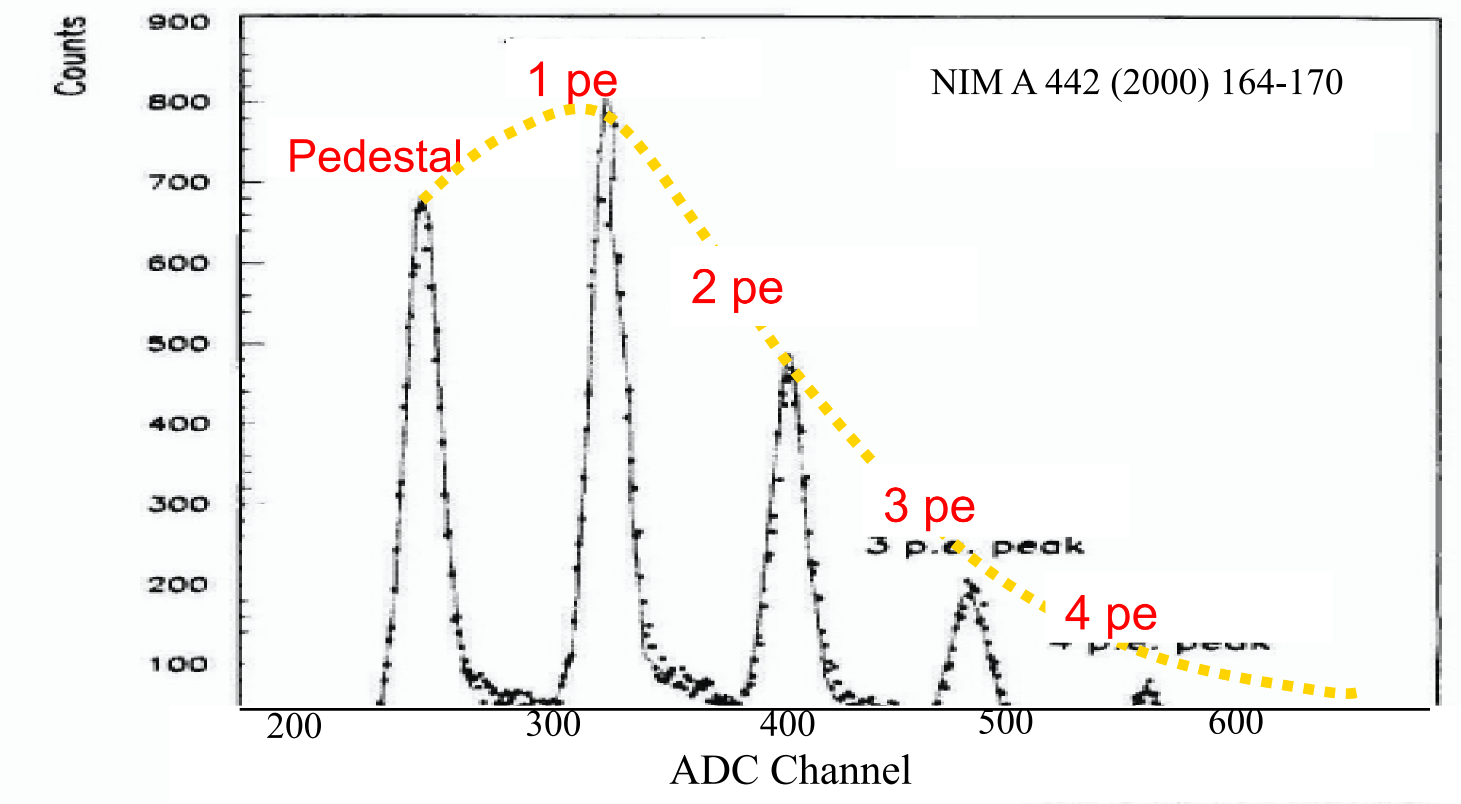


FAQ

- **When should we use PMT, and when should we use Silicon Photodiode?**
  - **Depends on intensity of photons.**
  - **Depends on speed of signals.**

Resolution of Hybrid Photodiode (HPD)

- HPD can count 1, 2, 3… PE separately.
  - δ_1 >1000, ENF=1.0

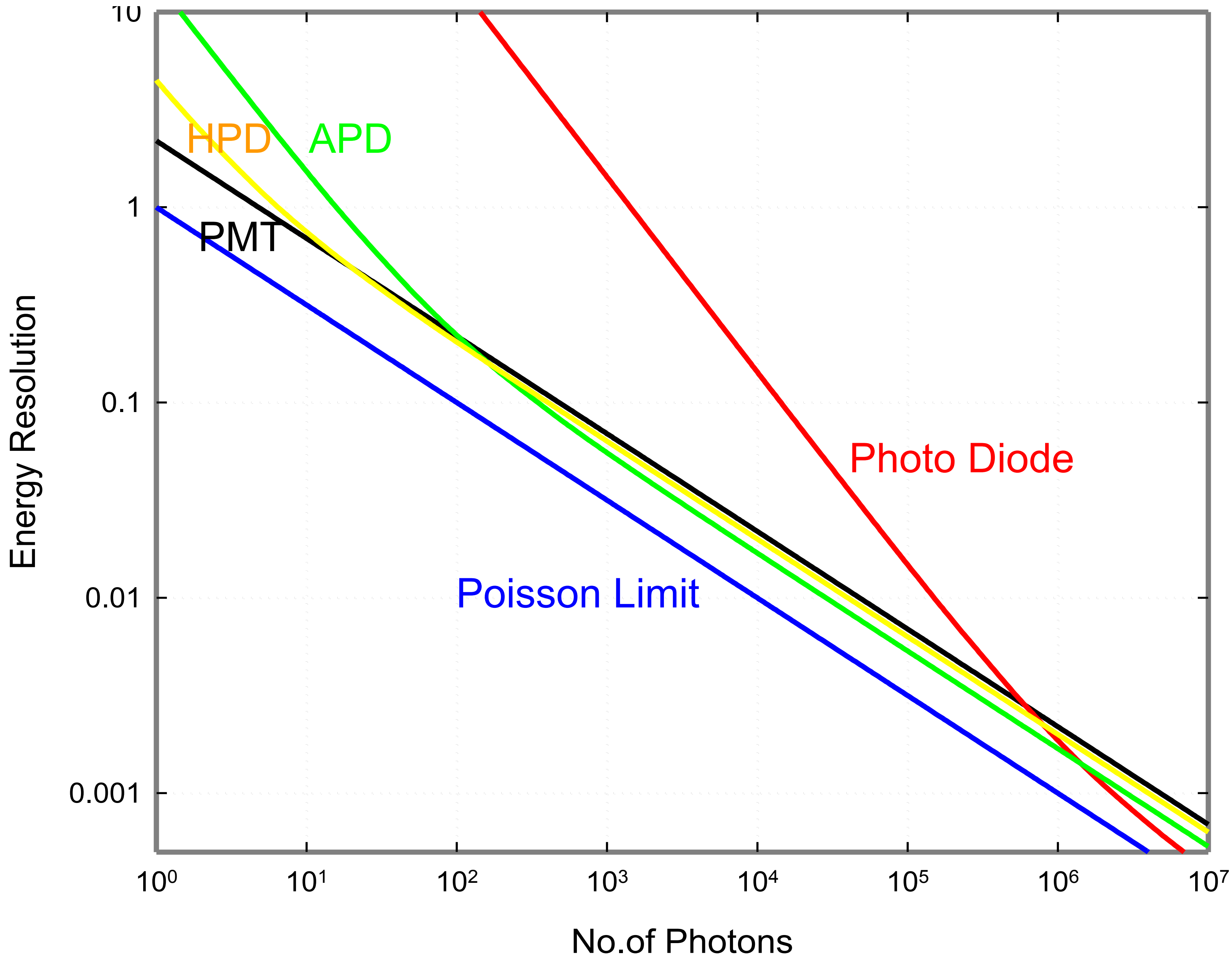


- But it is still suffering from poor QE.
  - We can never beat the Poisson statistics !

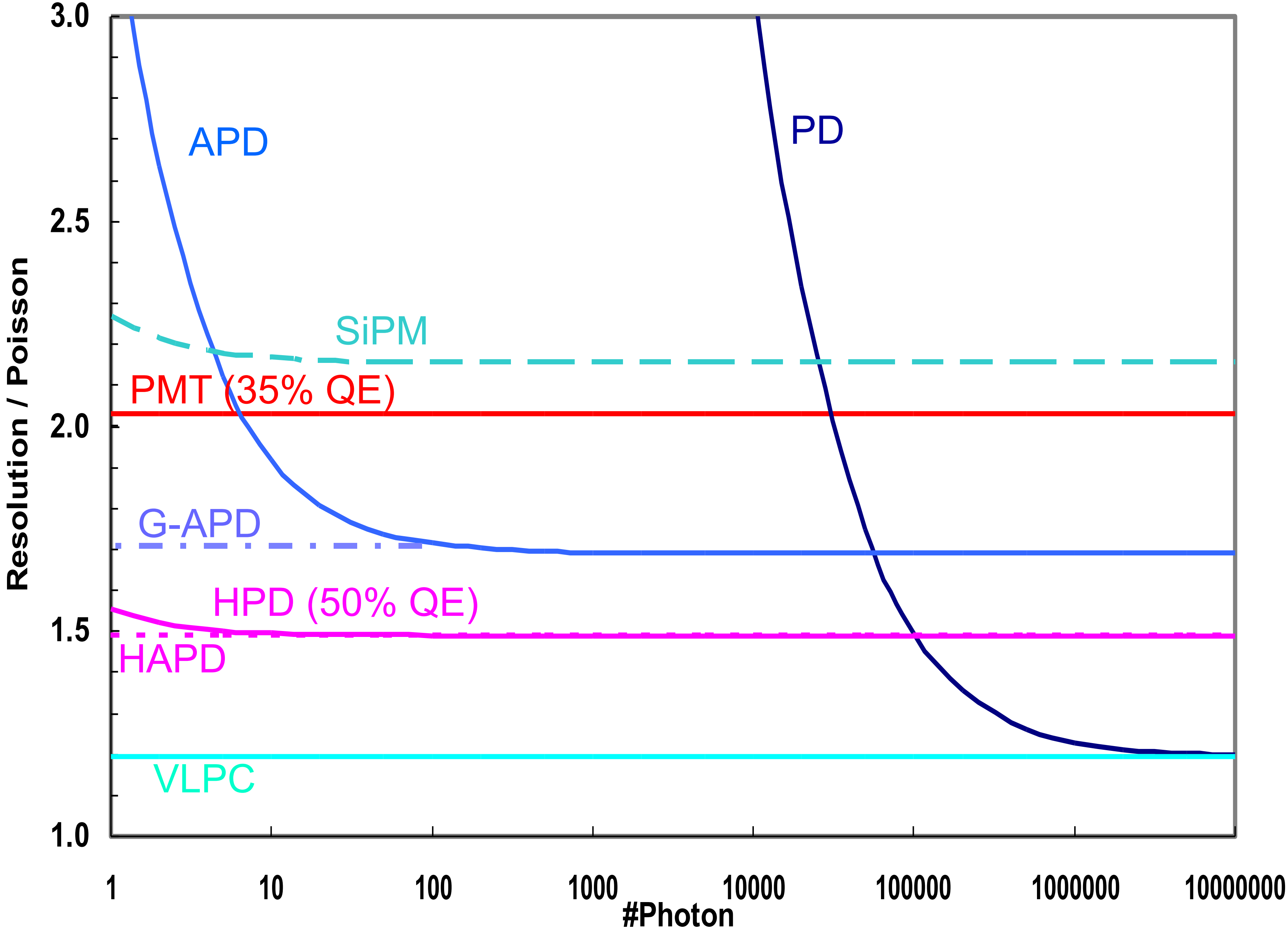
Summary Table

	QE	CE	δ_i	ENF	G	ENC	σ/E
Ideal	1.0	1.0	1000	1.0	10^6	0	$\sqrt{1/N}$
PMT	0.35	0.9	10	1.3	10^6	200	$\sqrt{3.8/N}$
PD	0.7	1.0	-	1.0	1	200	$\sqrt{1.4/N+(280/N)^2}$
APD	0.7	1.0	2	2.0	100	200	$\sqrt{2.9/N+(2.9/N)^2}$
HPD	0.5	0.9	1000	1.0	10^3	200	$\sqrt{2.2/N+(0.4/N)^2}$
HAPD	0.5	0.9	1000	1.0	10^5	200	$\sqrt{2.2/N}$
SiPM	0.7	0.4	1000	1.3	10^6	1000	$\sqrt{4.3/N}$
VLPC	0.7	1.0	1000	1.0	10^5	200	$\sqrt{1.4/N}$

Energy Resolution vs. N_γ



Resolution (over Poisson Limit)



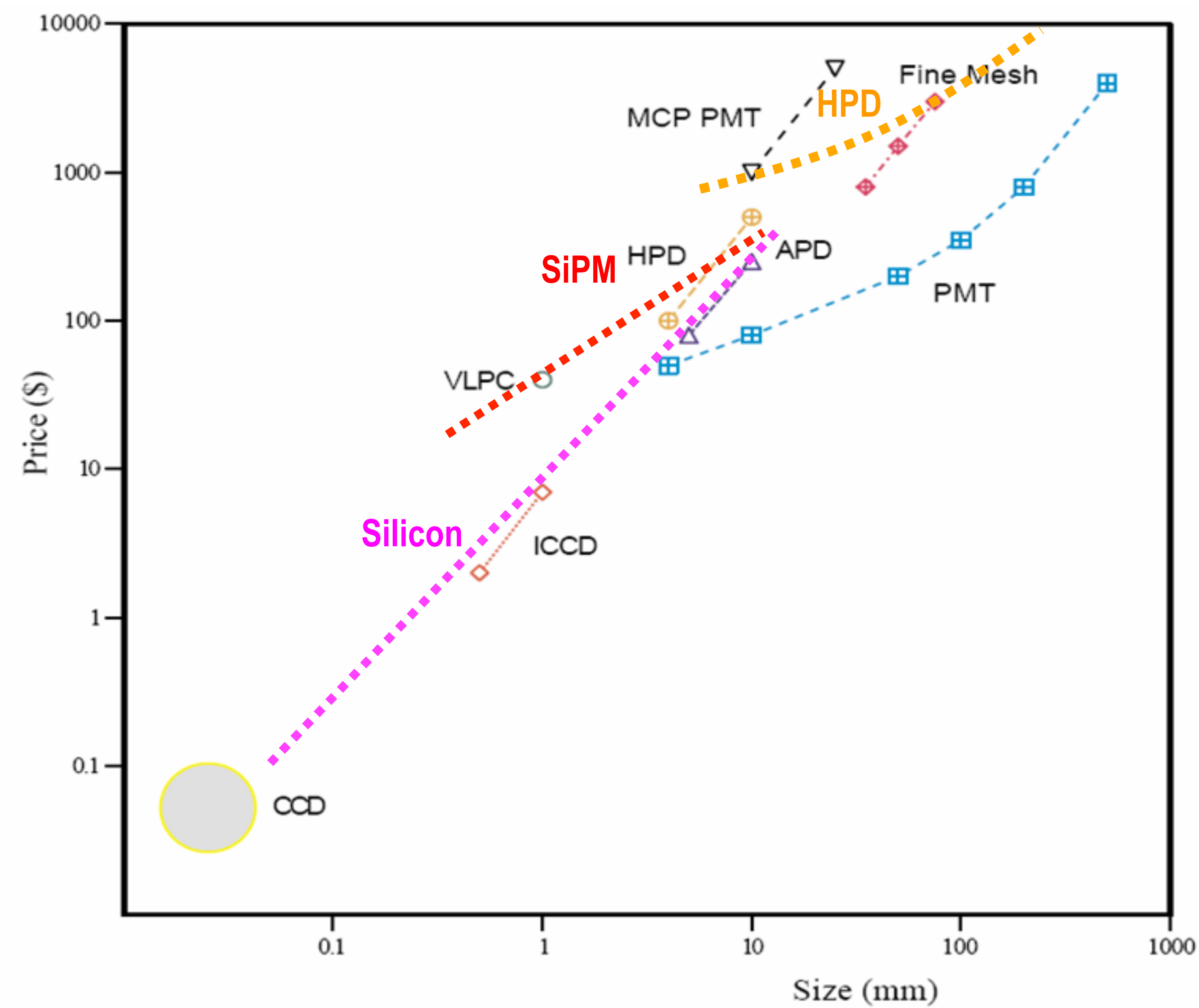
Summary

Purpose of Photon Detector

- Observe all the quantities of photons as accurate as possible.
  - The number of photons: E
  - Arrival time of photons: T
  - Position of photons: X, Y, Z

- Primary purpose of vacuum detectors:
  - Very small number of photons: < 100 photons
  - Accurate time of photons: < 10 nsec

Market Price



FAQ’s

- Why do we have to operate each PMT at different HV?
- Why is PMT response non-uniform over surface?
- What is the cause of non-linearity?
- How stable is PMT? How often should we calibrate? Every minute? Every day??
- What external facts could change the Gain of PMT?
- What could damage PMTs permanently?

More FAQ’s

- What is the source of dark current and dark pulse?
- Are they correlated?
- Why is PMT still the best for photon counting application?
- Why is APD or HPD not widely used?
- Then, who uses APD or HPD?
- Why is the signal of PMT so fast?

Closing Remarks

- PMTs are still used in many applications for good reasons:
  - Intrinsically high gain
  - Extremely low noise – photon counting
  - Fast speed (< 1 ns)
  - Large area (>> 5 inch)
- However PMTs are not perfect. There are many issues to be concerned:
  - Cathode and Anode Uniformity
  - Non Linearity
  - Effect of Magnetic Field
  - Long-term Stability

References

- **Hamamatsu PMT Handbook**
  - http://sales.hamamatsu.com/assets/applications/ETD/pmt_handbook_complete.pdf
- **Special thanks to**
  - Yuji Yoshizawa at Hamamatsu Photonics