Design and Commissioning of a Setup to Measure the Timing Resolution of Silicon Pixel Detectors

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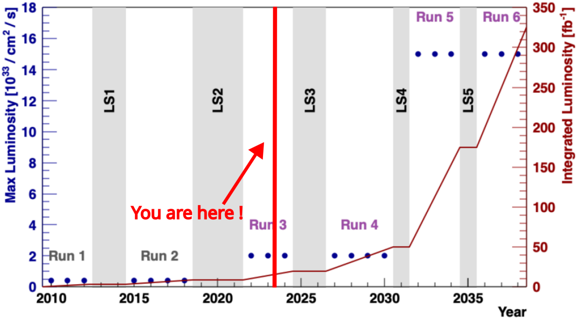
Planned LHC Luminosity Upgrade



LHCB-TDR-023

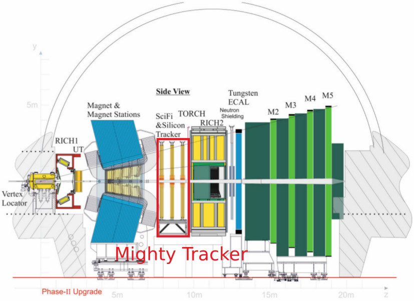
Implications for LHCb

- Luminosity increased to $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ after LS4

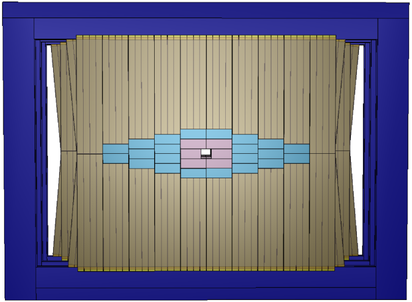
$\rightarrow$ Occupancy increased beyond design parameters

$\rightarrow$ Detector upgrades required

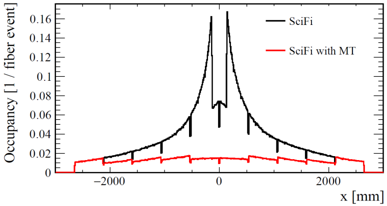
Downstream Tracker Upgrade



LHCB-TDR-023



LHCB-TDR-023



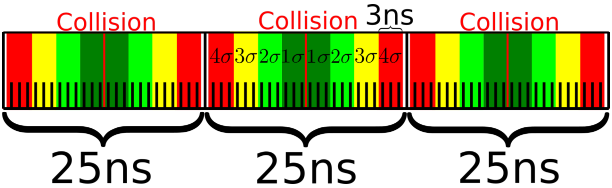
LHCB-TDR-023

Migthy Tracker

- Combination of scintillating fibres and pixel sensors
- Reduces occupancy below 2 %

→ Ensures good tracking performance

Why is the Timing Resolution Important?



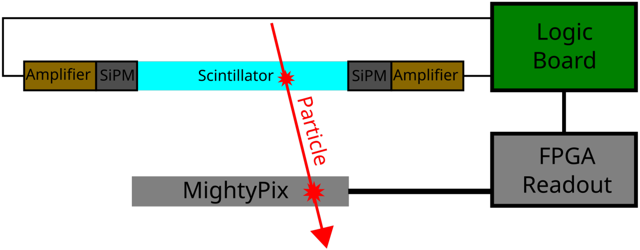
- 40 MHz bunchcrossing frequency $\Rightarrow$ 25 ns between collisions

$\rightarrow$ Timing resolution of $\approx$ 3 ns required to contain event within $\pm 4\sigma$

- So far measurements of timing resolution only possible at testbeam

$\rightarrow$ Develop setup for in-lab timing measurements

General Concept of the Timing Setup



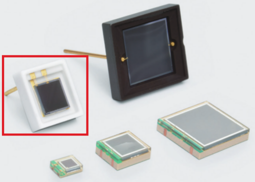
Design Criteria

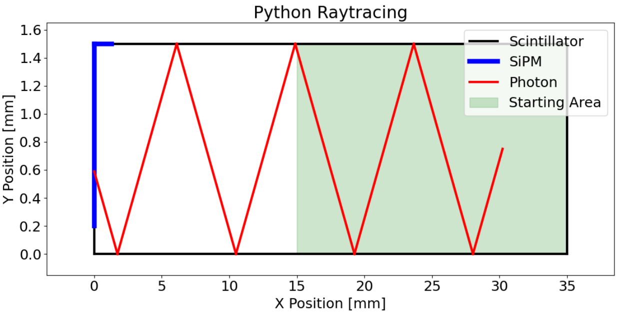
- Good timing resolution ⇒ silicon photomultipliers (SiPM) and fast plastic scintillator
- Versatile and modular
- Integrate seamlessly into existing FPGA readout (MARS)
- Low enough material budget to be used in front of sensor

→ Facilitates simple sensor cooling from the back

SiPM Selection and Positioning

Hamamatsu MPPC





SiPM Parameters

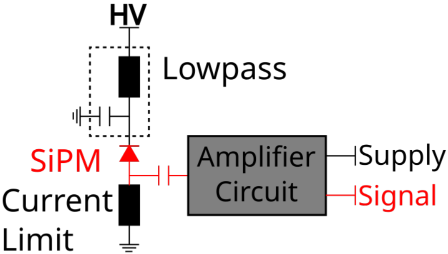
- Mounting type: SMD, THT
- Active area: $1.3 \times 1.3\ \text{mm}^2$, $3 \times 3\ \text{mm}^2$, $6 \times 6\ \text{mm}^2$
- Pixel pitch: 25 µm, 50 µm, 75 µm

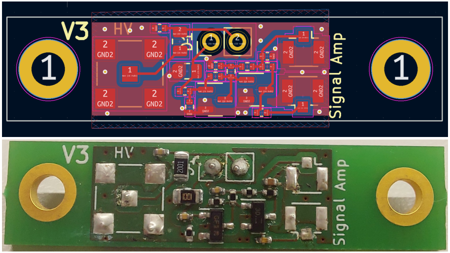
Simulation

- Random starting parameters
- Simulates propagation and reflections

$\rightarrow$ $3 \times 3\ \text{mm}^2$ with 50 µm pixel pitch mounted with legs

SiPM Readout and Amplifier Circuit

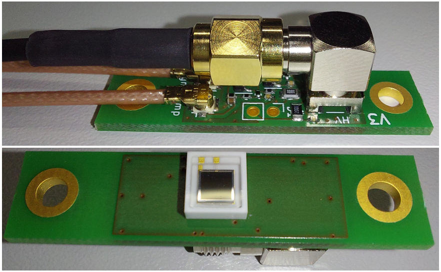


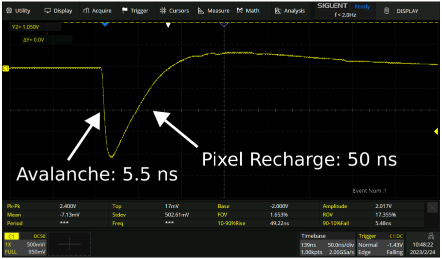


Features of the Amplifier Circuit

- Filters high voltage bias ⇒ reduce noise
- Capacitive coupling of signal to amplifier ⇒ isolates high voltage
- Amplification close to SiPM ⇒ improves signal to noise ratio
- Fast rise and fall time ⇒ enables high rates
- Positions SiPM

Amplifier PCB and Amplified SiPM Signal

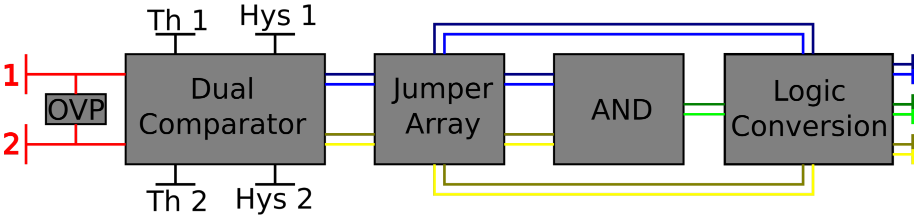




Implications of the Amplifier Circuit

- Large ratio of cable to PCB ⇒ need external strain relief
- SiPM obstructed by PCB ⇒ mount SiPM first
- Slow response time relative to desired time resolution ⇒ could be bottleneck

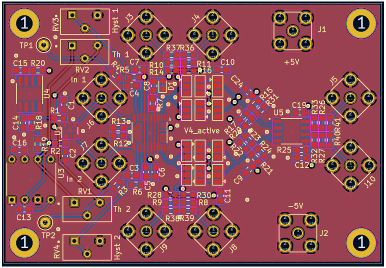
How to Handle Digitization and Signal Processing?

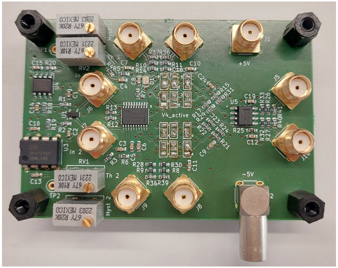


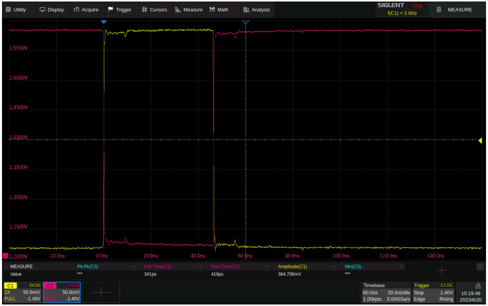
Features of the Logic Board

- Two inputs with over voltage protection
- Dual comparator with adjustable thresholds and hysteresis ⇒ digitization of signals
- Output selection via jumper array ⇒ reduce noise
- Differential AND ⇒ coincidence of SiPMs
- Logic conversion from PECL to LVDS ⇒ interface with FPGA readout

Logic Board





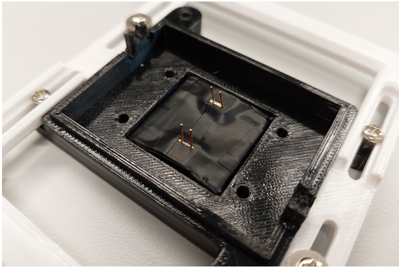


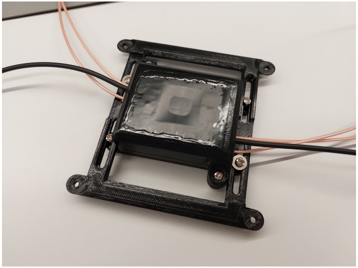
Signal Characteristics

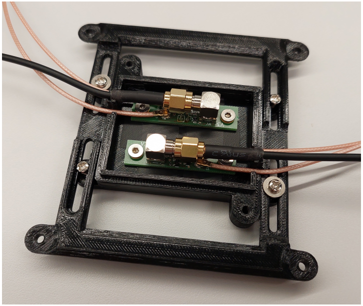
- Little Noise ⇒ may be a reflection
- Rise/fall time ≈0.4 ns
- 1.2 V logic low and 1.6 V logic high

⇒ may work with FPGA

Mechanical Structure



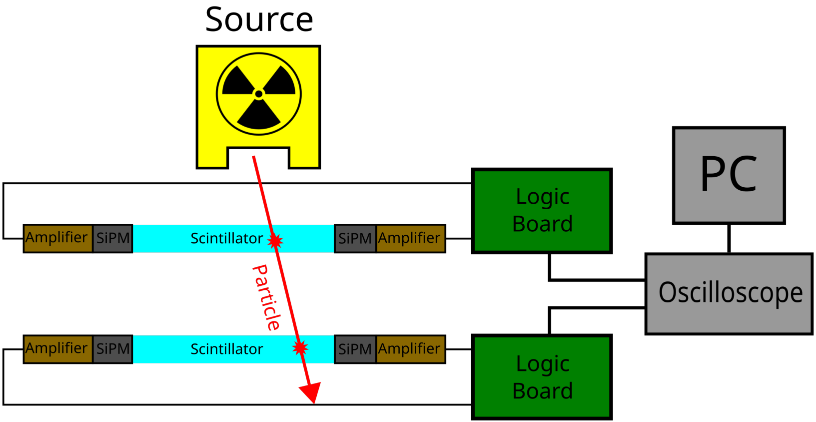




Requirements

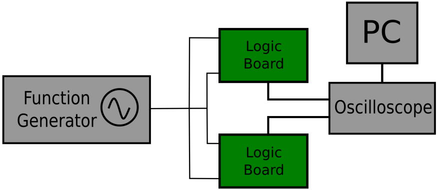
- 3D printed
- Mounts two amplifier boards
- Is light tight by itself
- Holds scintillator
- Little additional material budget

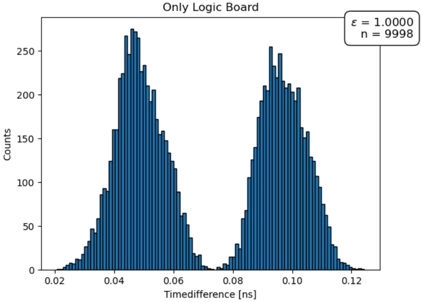
Setup to Measure Timing Resolution



- Source above two timing layers
- Trigger on coincidence signal of lower layer
- Automated data taking with PC and Oscilloscope

Performance of Logic Board

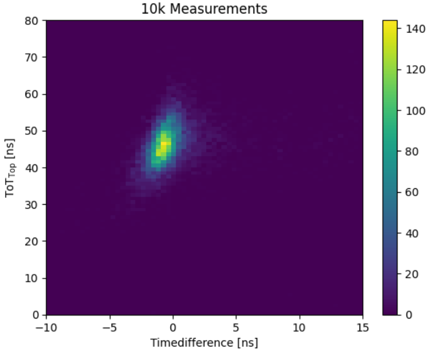


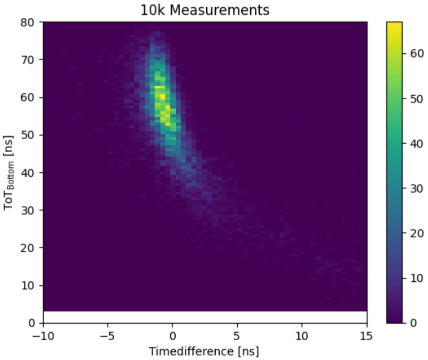


Observations

- Double peak ⇒ may be related to sampling rate / artifact of quantized measurement or signal of function generator
- Timing resolution on the order of 0.1 ns ⇒ logic board should not bottleneck performance

Shape of Timing Resolution

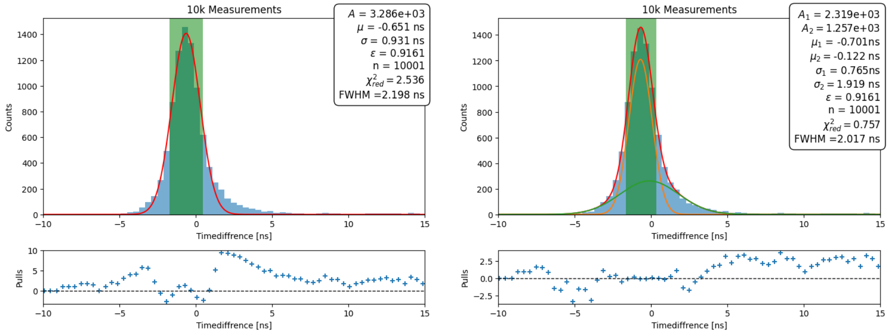




Observations

- Curvature of distribution ⇒ follows expectation for time walk
- Lower ToT reached in bottom layer ⇒ particles stopped in layer
- Difference in maximum ToT ⇒ partly explained by different response of timing layers to deposited energy

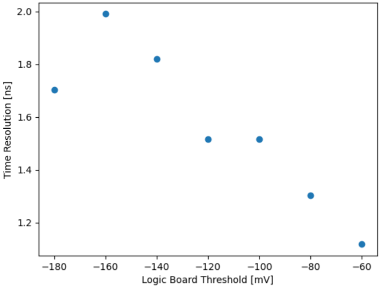
Determining a Single Value for the Time Resolution

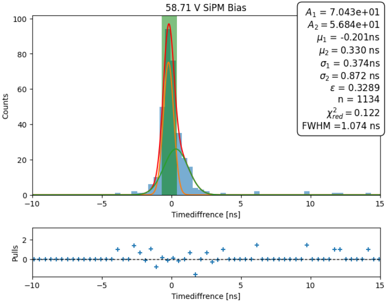


Considerations

- Not a simple Gaussian
- Empirical fit function needed ⇒ sum of two Gaussians describes data
- Timing resolution can be expressed as FWHM of distribution
- Timing resolution of a single layer: $\frac{1}{\sqrt{2}}\mathrm{FWHM}$

Ongoing Work

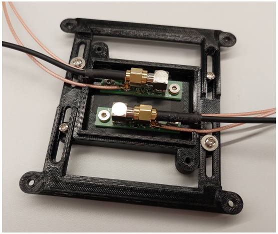


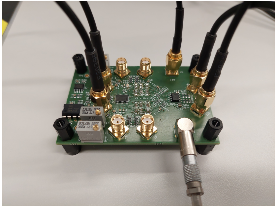


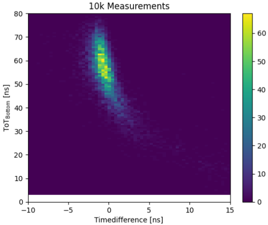
Parameters to Optimize

- Supply voltage of Amplifier ⇒ balancing heating and fall time of signal
- SiPM bias ⇒ trade off between gain and noise
- Threshold ⇒ reducing time walk while avoiding noise floor
- Best so far: $\mathrm{FWHM} = 1.074\,\mathrm{ns} \mathrel{\hat{=}} \sigma_{single} = 0.759\,\mathrm{ns}$

Future Topics to Explore







Hardware Improvements

- FPGA integration
- Streamline powering
- Increase active area
- Design faster amplifier
- Use faster scintillator
- Time walk correction

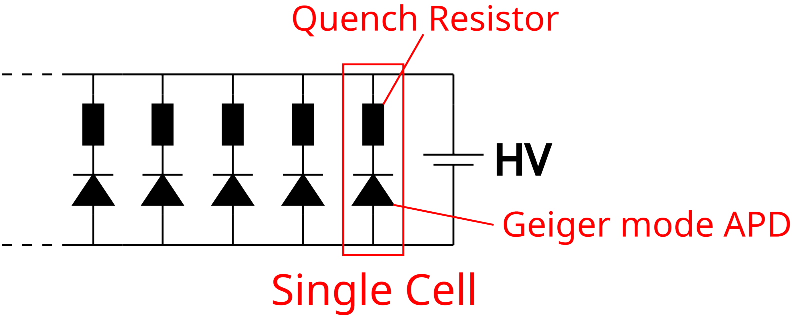
Additional Measurements

- Performance at different temperatures
- Noise immunity
- Testbeam
- Radiation hardness

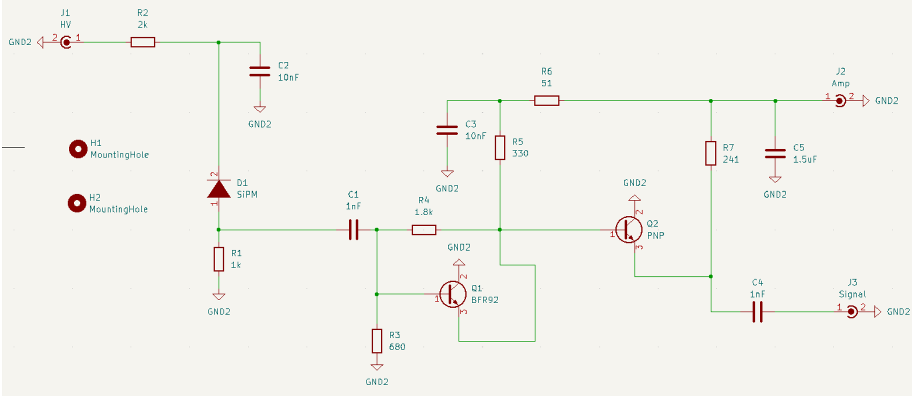
Thank you!

Questions?

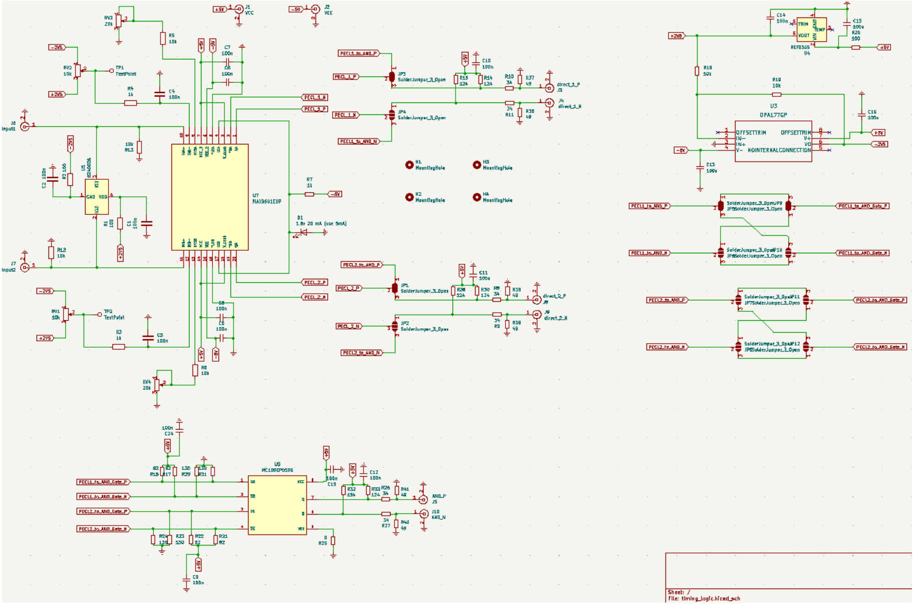
SiPM



SiPM Amplifier Circuit Schematic



Logic Board Schematic



Selection guide

Type no.	Pixel pitch (μm)	Effective photosensitive area (mm)	Number of pixels	Package	Fill factor (%)
S13360-1325PE	25	1.3 × 1.3	2668	Glass epoxy	47
S13360-3025CS		3.0 × 3.0	14400	Ceramic	
S13360-3025PE				Glass epoxy	
S13360-6025CS		6.0 × 6.0	57600	Ceramic	
S13360-6025PE				Glass epoxy	
S13360-1350PE	50	1.3 × 1.3	667	Glass epoxy	74
S13360-3050CS		3.0 × 3.0	3600	Ceramic	
S13360-3050PE				Glass epoxy	
S13360-6050CS		6.0 × 6.0	14400	Ceramic	
S13360-6050PE				Glass epoxy	
S13360-1375PE	75	1.3 × 1.3	285	Glass epoxy	82
S13360-3075CS		3.0 × 3.0	1600	Ceramic	
S13360-3075PE				Glass epoxy	
S13360-6075CS		6.0 × 6.0	6400	Ceramic	
S13360-6075PE				Glass epoxy	

Structure / Absolute maximum ratings

Type no. (package)	Window material	Refractive index of window material	Absolute maximum ratings			
			Operating temperature*1 Topr (°C)	Storage temperature*1 Tstg (°C)	Soldering temperature	Reflow soldering temperature Tsol
S13360-****CS (ceramic)	Silicone resin	1.41	-20 to +60	-20 to +80	350 °C*2	-
S13360-****PE (glass epoxy)	Epoxy resin	1.55			-	Peak temperature: 240 °C*3

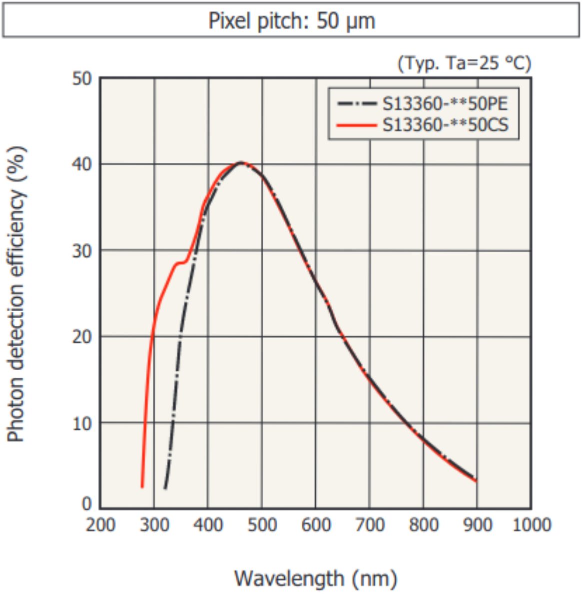
Hamamatsu MPPC

Electrical and optical characteristics (Typ. Ta=25 °C, unless otherwise noted)

Type no.	Measurement conditions	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photon detection efficiency PDE*4 λ=λp (%)	Dark count*5 Typ. (kcps)	Dark count*5 Max. (kcps)	Terminal capacitance Ct (pF)	Gain M	Breakdown voltage V_{BR} (V)	Crosstalk probability (%)	Recommended operating voltage Vop (V)	Temperature coefficient at recommended operating voltage ΔTVop (mV/°C)
S13360-1325PE	Vover =5 V	320 to 900	450	25	70	210	60	7.0×10^5	53 ± 5	1	V_{BR} + 5	54
S13360-3025CS		270 to 900			400	1200	320					
S13360-3025PE		320 to 900										
S13360-6025CS		270 to 900			1600	5000	1280					
S13360-6025PE		320 to 900										
S13360-1350PE	Vover =3 V	320 to 900		40	90	270	60	1.7×10^6		3	V_{BR} + 3	
S13360-3050CS		270 to 900			500	1500	320					
S13360-3050PE		320 to 900										
S13360-6050CS		270 to 900			2000	6000	1280					
S13360-6050PE		320 to 900										
S13360-1375PE	Vover =3 V	320 to 900		50	90	270	60	4.0×10^6		7	V_{BR} + 3	
S13360-3075CS		270 to 900			500	1500	320					
S13360-3075PE		320 to 900										
S13360-6075CS		270 to 900			2000	6000	1280					
S13360-6075PE		320 to 900										

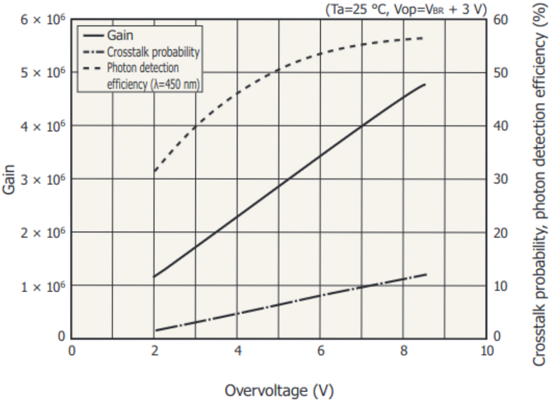
*4: Photon detection efficiency does not include crosstalk or afterpulses.
*5: Threshold=0.5 p.e.
Note: The above characteristics were measured at the operating voltage that yields the listed gain. (See the data attached to each product.)

Hamamatsu MPPC



Hamamatsu MPPC

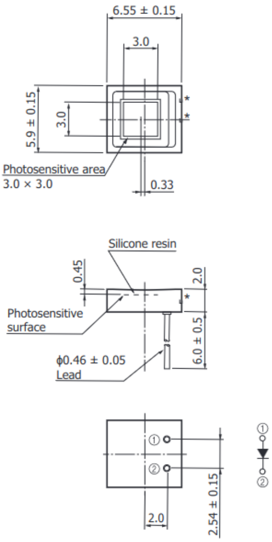
Pixel pitch: 50 μm



Hamamatsu MPPC

Dimensional outlines (unit: mm)

S13360-3025CS/-3050CS/-3075CS



Lead material: Oxygen-free copper
Lead processing: Au plating
Tolerance unless otherwise noted: ±0.2
Chip position accuracy:
with respect to package center
-0.25≤X≤+0.25
-0.53≤Y≤-0.13
The coating resin may extend a maximum of
0.1 mm above the upper surface of the package.

* Metal electrodes connecting to the internal electrodes are exposed on the sides of the ceramic package. To avoid short circuits, never allow other conductors to come in contact with these metal electrodes.

Hamamatsu MPPC

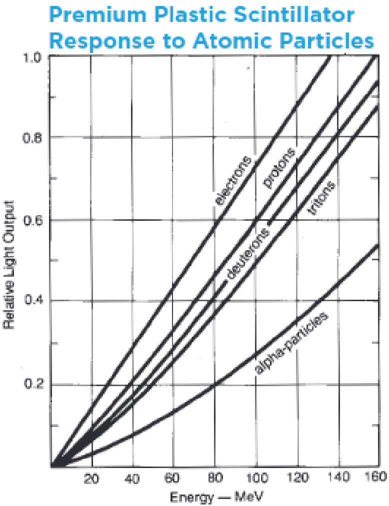
	BC-400	BC-404	BC-408	BC-412	BC-416
Principal Uses/Applications	general purpose	fast counting	TOF large area	large area	large area economy
Scintillation Properties					
Light Output, %Anthracene	65	68	64	60	38
Rise Time, ns	0.9	0.7	0.9	1.0	-
Decay Time (ns)	2.4	1.8	2.1	3.3	4.0
Pulse Width, FWHM, ns	2.7	2.2	-2.5	4.2	5.3
Wavelength of Max. Emission, nm	423	408	425	434	434
Light Attenuation Length, cm*	160	140	210	210	210
Bulk Light Attenuation Length, cm	250	160	380	400	400
Atomic Composition					
No. H Atoms per cc ($x10^{22}$)	5.23	5.21	5.23	5.23	5.25
No. C Atoms per cc ($x10^{22}$)	4.74	4.74	4.74	4.74	4.73
Ratio H:C Atoms	1.103	1.100	1.104	1.104	1.110
No. of Electrons per cc ($x10^{23}$)	3.37	3.37	3.37	3.37	3.37

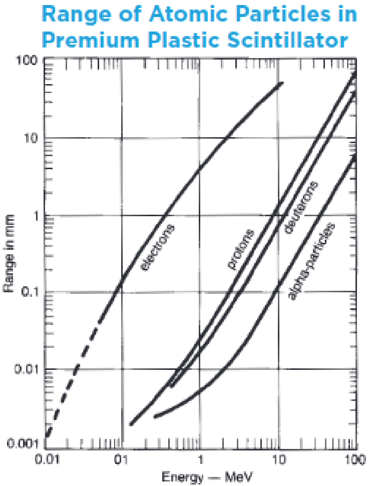
*The typical 1/e attenuation length of a 1x20x200cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end.

General Technical Data –

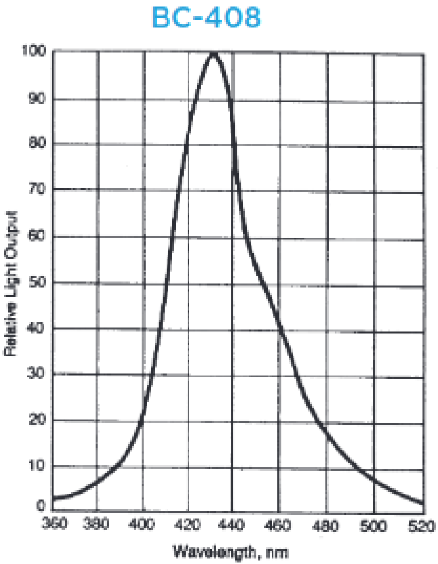
Base	Polyvinyltoluene	Vapor Pressure	May be used in vacuum
Density [g/cc]	1.023	Light Output	At +60°C = 95% of that at+20°C. Independent of temperature from -60°C to +20°C
Expansion Coefficient (per°C,<67°C)	$7.8X10^{-5}$	Solubility	Soluble in aromatic solvents, chlorinated solvents, acetone, etc. Unaffected by water, dilute acids, lower alcohols, alkalis and pure silicone fluids or grease.
Refractive index	1.58		
Softening Point	70°C		

Saint Gobain



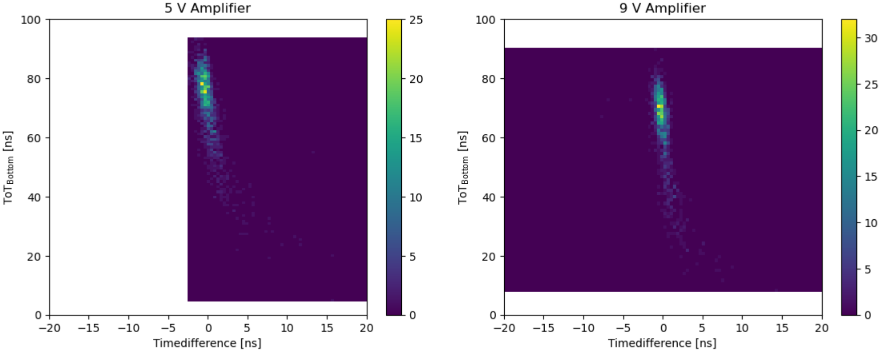


Saint Gobain



Saint Gobain

Further Uses of 2D Histogram



Larger Supply Voltage of Amplifier

- steeper and narrower distribution $\Rightarrow$ better timing resolution