Characterization of Position Measurement Error, Position Resolution and Photoelectron Number Resolution for Position-Sensitive SiPMs

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Outline

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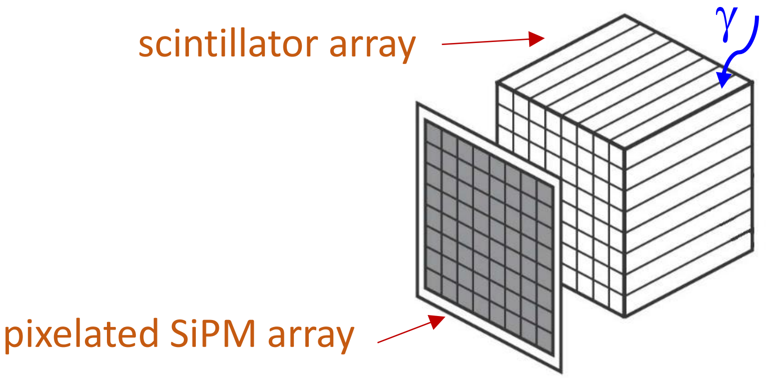
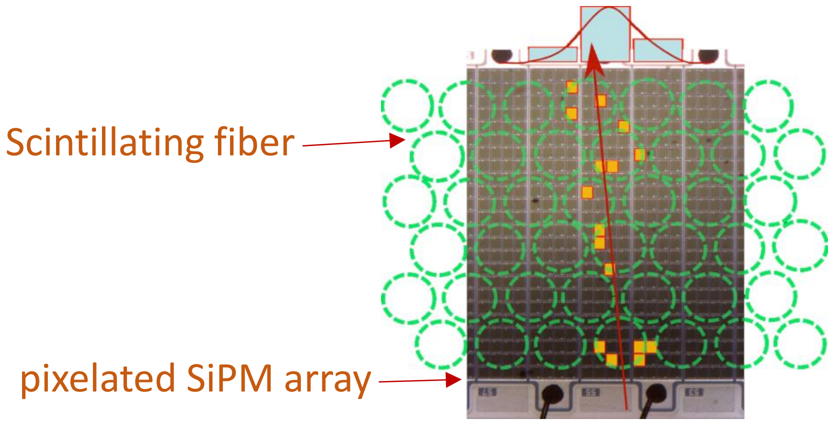
- Definitions and Concepts
- Measurement Method and Setup
- Results
  - Position Measurement Error
  - Position Resolution
  - Photoelectron Number Resolution
- Conclusion

Backgrounds

- Scintillation imaging sensors based on pixelated SiPMs suffered low space resolution, large amount of readout channels, leading high cost, low reliability and limitation of applications.
- One alternative is to use position sensitive (PS) SiPMs substituting conventional SiPM pixels.
- Position Measurement Error (PME), Position Resolution and Photoelectron Number Resolution (PNR) are key parameters of PS-SiPM, a well-known technique to characterize those parameters hasn't been established.



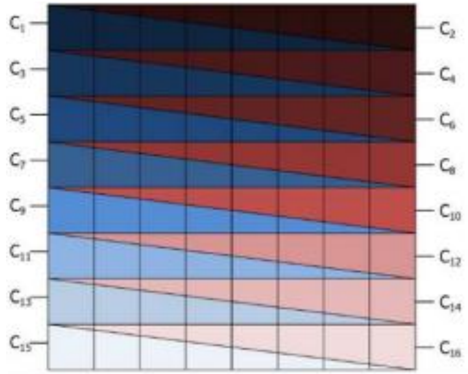
Pixelated SiPM array for the readout of PET detector



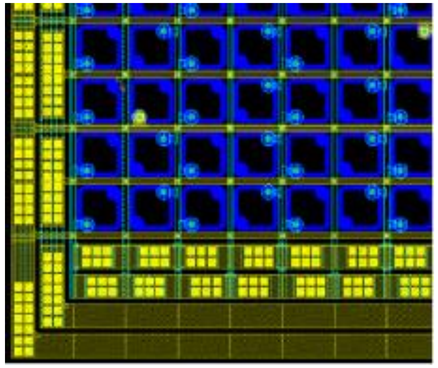
Pixelated SiPM array in a Scintillating Tracker in HEP

PS-SiPM in Publications

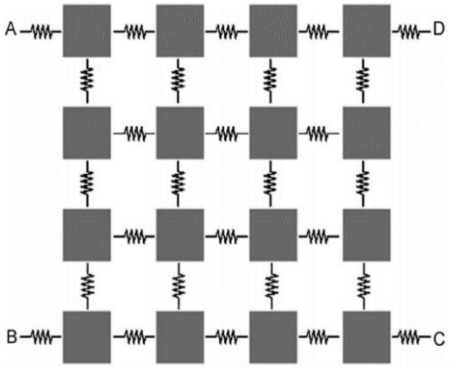
SeSP Uni. of Aachen, Germany [1]



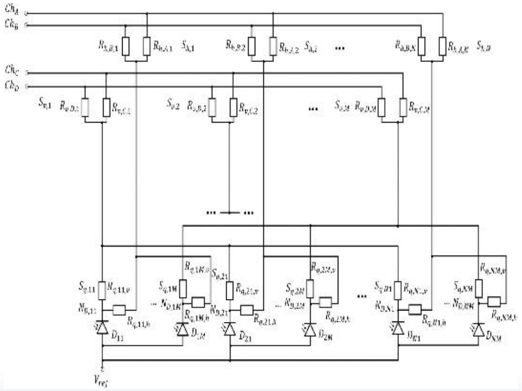
ISiPM Univ. of Heidelberg, Germany[2]



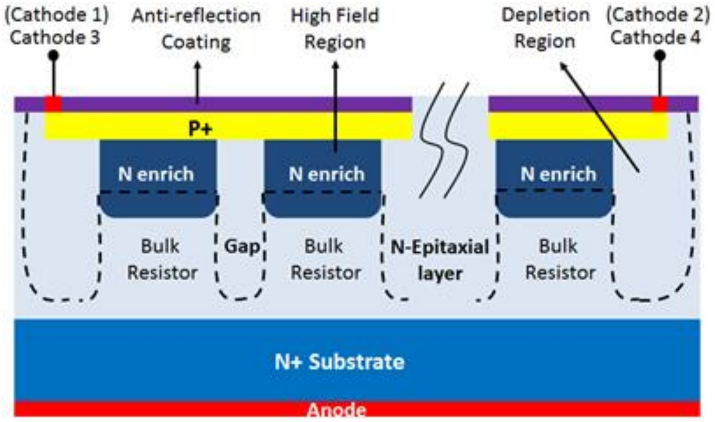
PS-SSPM RMD, USA [3]

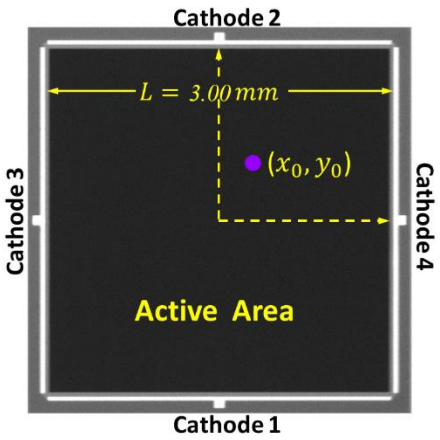


LG-SiPM FBK, Italy [4]



NDL EQR-SiPM → CRL-SiPM [5]





References

[1] Omidvari, N. and V. Schulz, IEEE Transactions on Nuclear Science, 2015. 62(3): p. 679-687.

[2] I., S., et al. IEEE SENSORS. 2013.

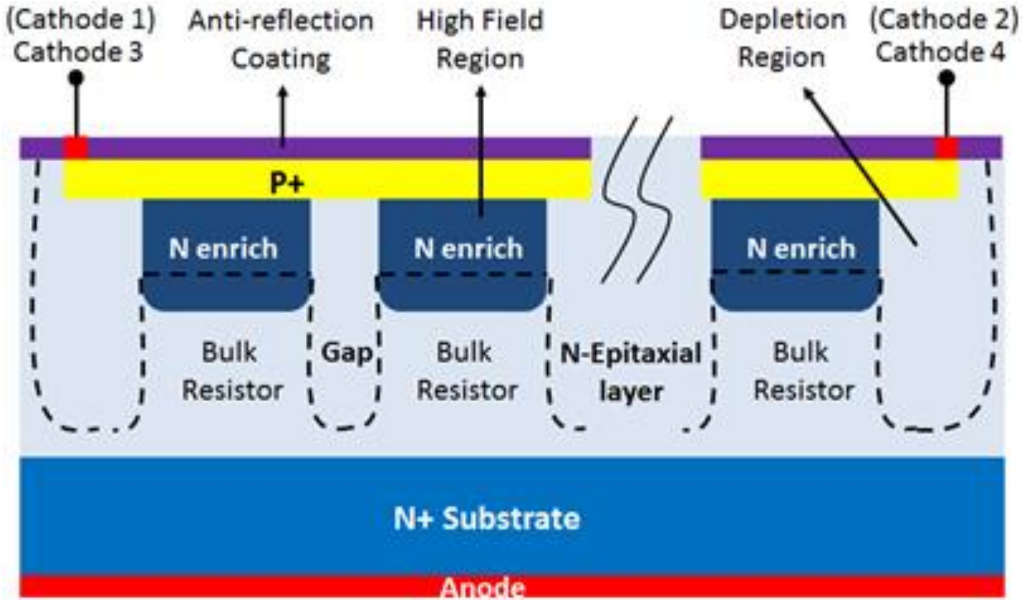
[3] J., P.S., et al., IEEE Transactions on Nuclear Science, 2014. 61(3): p. 1074-1083.

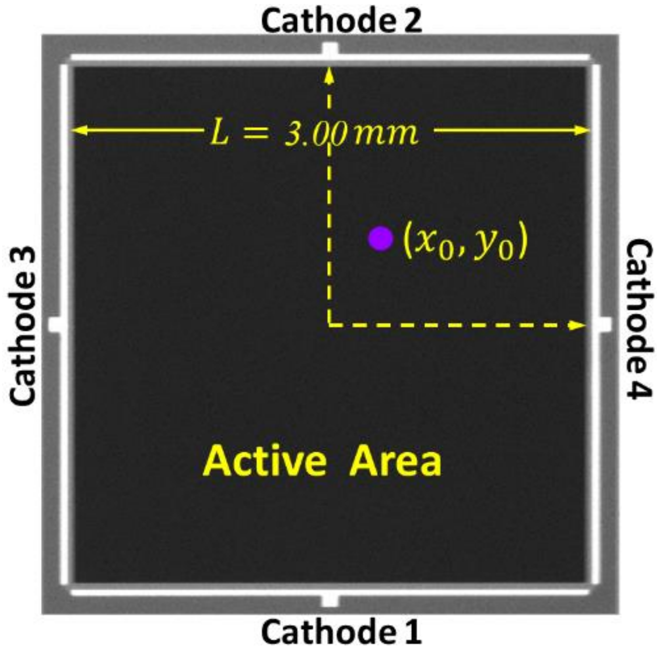
[4] Berneking, A., et al., NIM:A, 2018. 888: p. 44-52.

[5] Zhao, T., et al., IEEE Electron Device Letters, 2017. 38(2): p. 228-231.

Brief Introduction to NDL SiPMs

- In the past ~10 years, NDL has developed a novel SiPM technology, i.e., a SiPM with epitaxial quenching resistors (EQR). It has advantages such as high micro cell density (thus large dynamic range) while retaining high photon detection efficiency (PDE), simple fabrication technology and cost effective.
- EQR-SiPM features a cap resistive layer (CRL) to connect all the micro APD cells, thus is easy to implement for charge division mechanism and realize a PS-SiPM.





NDL SiPM Parameters

Series	Description	Cell number per pixel	Pixel active area(mm^2)
11-1010C	Regular	10000	1.0 × 1.0
11-3030C	Regular	90000	3.0 × 3.0
11-2727PS	Position Sensitive	76730	2.77 × 2.77

Active area (mm^2)	1.0 × 1.0 ~ 3.0 × 3.0	**Gain**	$\geq 2\times10^5$
Microcell density	~ 10000 /mm^2	**Dark count rate**	< 600 kHz/mm^2
Peak PDE	> 31%@420 nm	**Single photon time resolution**	50 - 200 ps
Temperature coefficient for Vb	25 mV/°C	**Optical crosstalk**	< 7%
Breakdown voltage	27.5 ± 0.4 V	**Max over-voltage**	8 V

www.ndl-sipm.net

Definitions and Concepts

- **PME**: the deviation between the true light spot position and the measured one

$$PME_i = \sqrt{\left(\bar{x}_i - X_i\right)^2 + \left(\bar{y}_i - Y_i\right)^2}$$

$$\text{Mean PME} = \frac{\sum_{i=1}^{n} PME_i}{n}$$

$\bar{x}, \bar{y}$: measured position which is determined by the average value of position coordinates obtained from a position algorithm

X, Y : true position

i, n : label and number of measured position, respectively

- **Position Resolution (PR)**: FWHM of the measured position distribution and is determined mainly by the intrinsic position resolution of the device, the fluctuation of the barycenter of the light spot and the contribution from electronic noises of measurement system.

$$PR_{System,i}{}^2 = PR_{Device,i}{}^2 + FWHM_{Photons}{}^2 + PR_{Electronics}{}^2$$

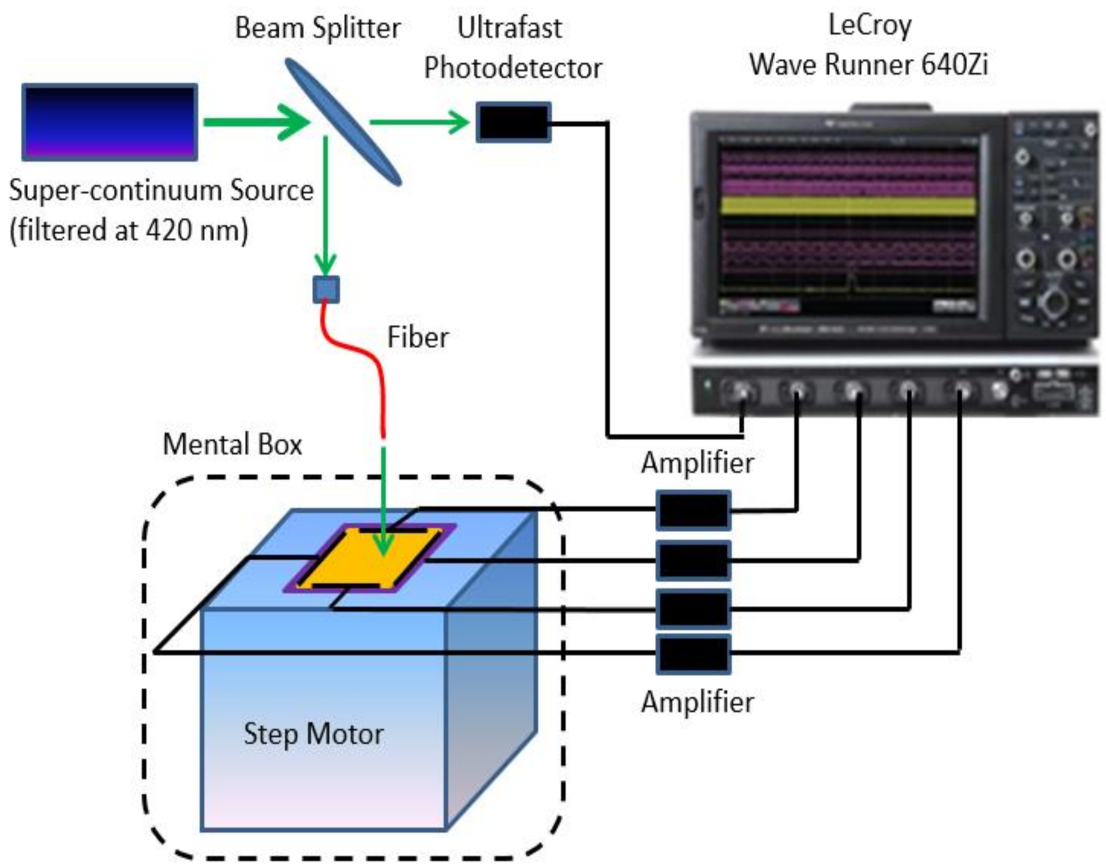
Definitions and Concepts

- **Photoelectron Number Resolution** : the most photoelectron number that can be discriminated in a light pulse, it can be determined by the photoelectron pulse area distribution of the SiPMs (e.g., total pulse area distribution of 4 cathodes in CRL-SiPM).

  - Regular SiPMs, along with NDL CRL-SiPM, have perfect photoelectron number discriminating capability, single photoelectron resolving is usually not a problem.

  - Only "how many photoelectrons that can be resolved" makes sense, it determines the real photoelectron resolving capability of the device!

Measurement Method and System



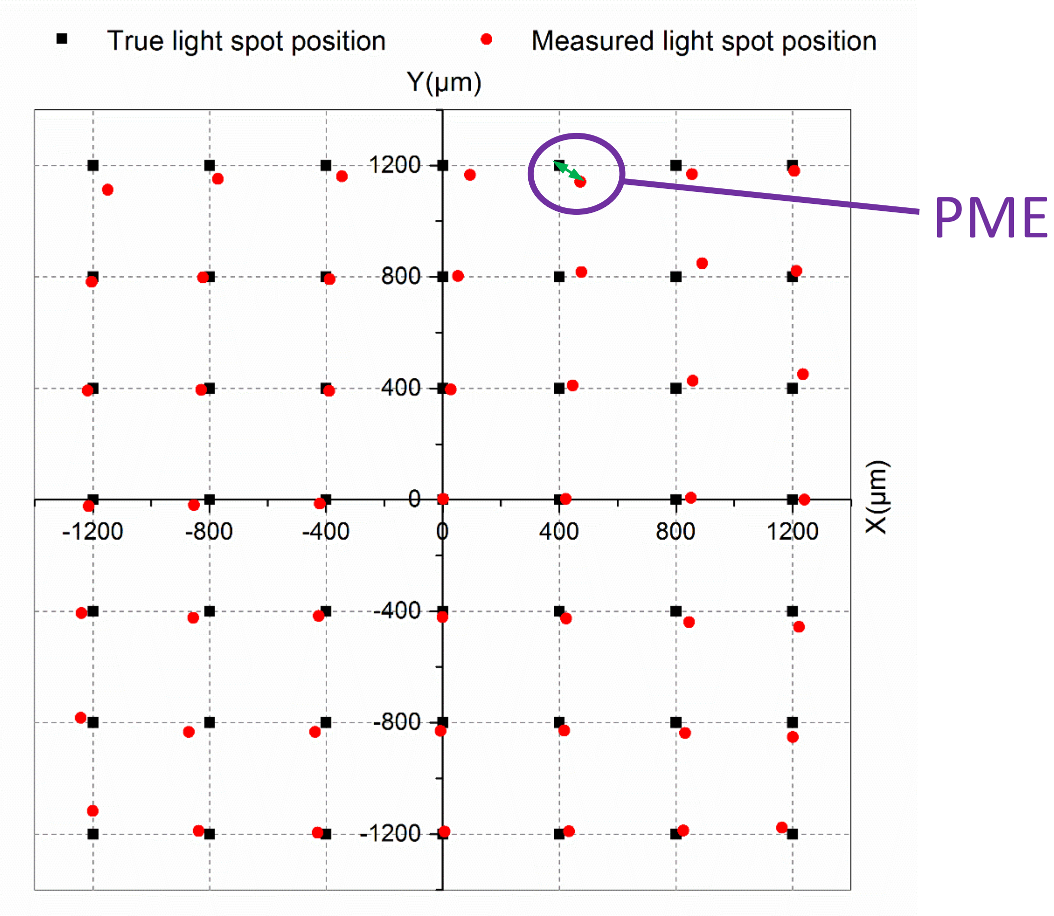
Setup of the measurement system

- Light pulse from the fiber follows the Gauss distribution, the diameter of the light spot can be measured by using knife-edge scanning method (~80 µm @MPEN≈5 in this work).

- The device was fixed on a micro positioner with positional accuracy of 1 µm. The active area of the device was scanned from one edge to another (−1200 µm, −1200 µm) to (1200 µm, 1200 µm) by using the incident light with proper steps (200 µm, or 400 µm) and intensity.

- At each incident light position, 5000 sets of pulse area or amplitude (Q_j , j = 1 − 4) data are recorded for the 4 cathodes.

Results—Position Measurement Error



The deviation of measured light spot positions (red points) from true light spot positions (black points)

$$PME_i = \sqrt{\left(\overline{x}_i - X_i\right)^2 + \left(\overline{y}_i - Y_i\right)^2} \qquad \text{Mean PME} = \frac{\sum_{i=1}^{n} PME_i}{n}$$

The Position Algorithm for CRL-SiPM [5]

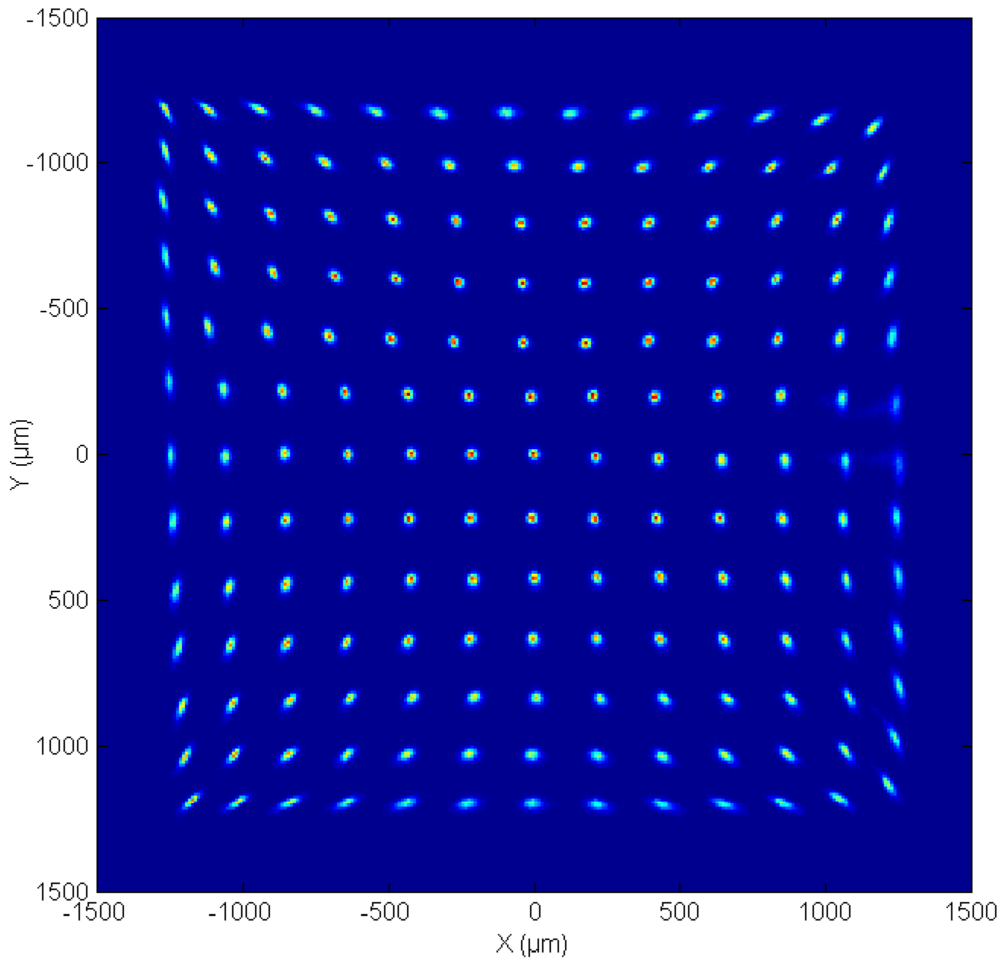
$$x = \frac{L}{2} \bullet \frac{\left(\frac{R_0}{R_S}+8.7492\right)(Q_4-Q_3)\left[\left(\frac{1.7R_0}{R_S}+5.8156\right)(Q_1+Q_2)+\left(\frac{R_0}{R_S}-5.8156\right)(Q_3+Q_4)\right]}{\left[\frac{R_0}{R_S}(Q_1+Q_2+Q_3+Q_4)\right]^2-\left[1.02\left(\frac{R_0}{R_S}+8.7492\right)(Q_2-Q_1)\right]^2}$$

$$y = \frac{L}{2} \bullet \frac{\left(\frac{R_0}{R_S}+8.7492\right)(Q_2-Q_1)\left[\left(\frac{R_0}{R_S}-5.8156\right)(Q_1+Q_2)+\left(\frac{1.7R_0}{R_S}+5.8156\right)(Q_3+Q_4)\right]}{\left[\frac{R_0}{R_S}(Q_1+Q_2+Q_3+Q_4)\right]^2-\left[1.02\left(\frac{R_0}{R_S}+8.7492\right)(Q_4-Q_3)\right]^2}$$

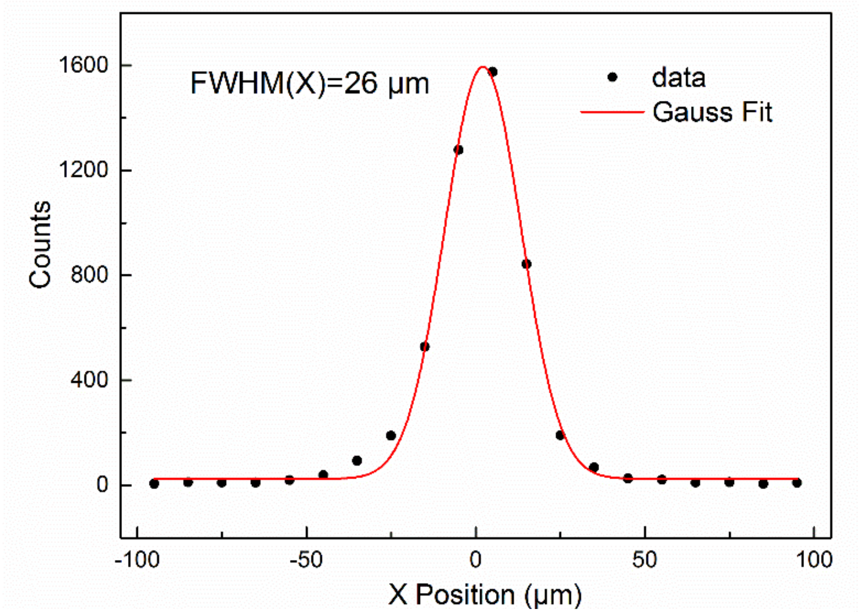
L: the length of the active area (3 mm in this work)
Rs: the input impedance (50 Ω)
R_0: sheet impedance (320 Ω)
Q_j (j = 1, 2, 3, 4): the shared charge of the corresponding cathode

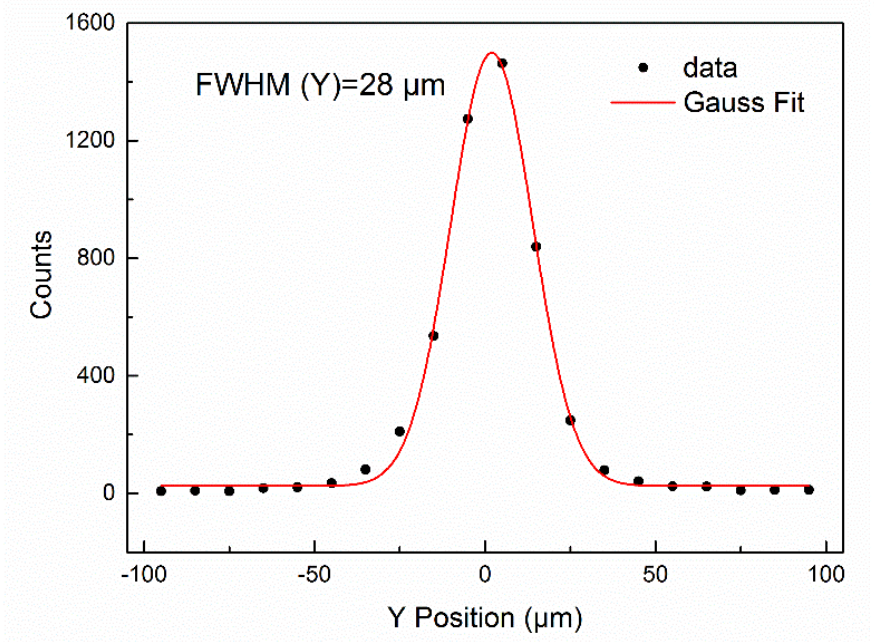
In this work, PME_{device} = 45.4 ± 24.4 μm

Results—Position Resolution



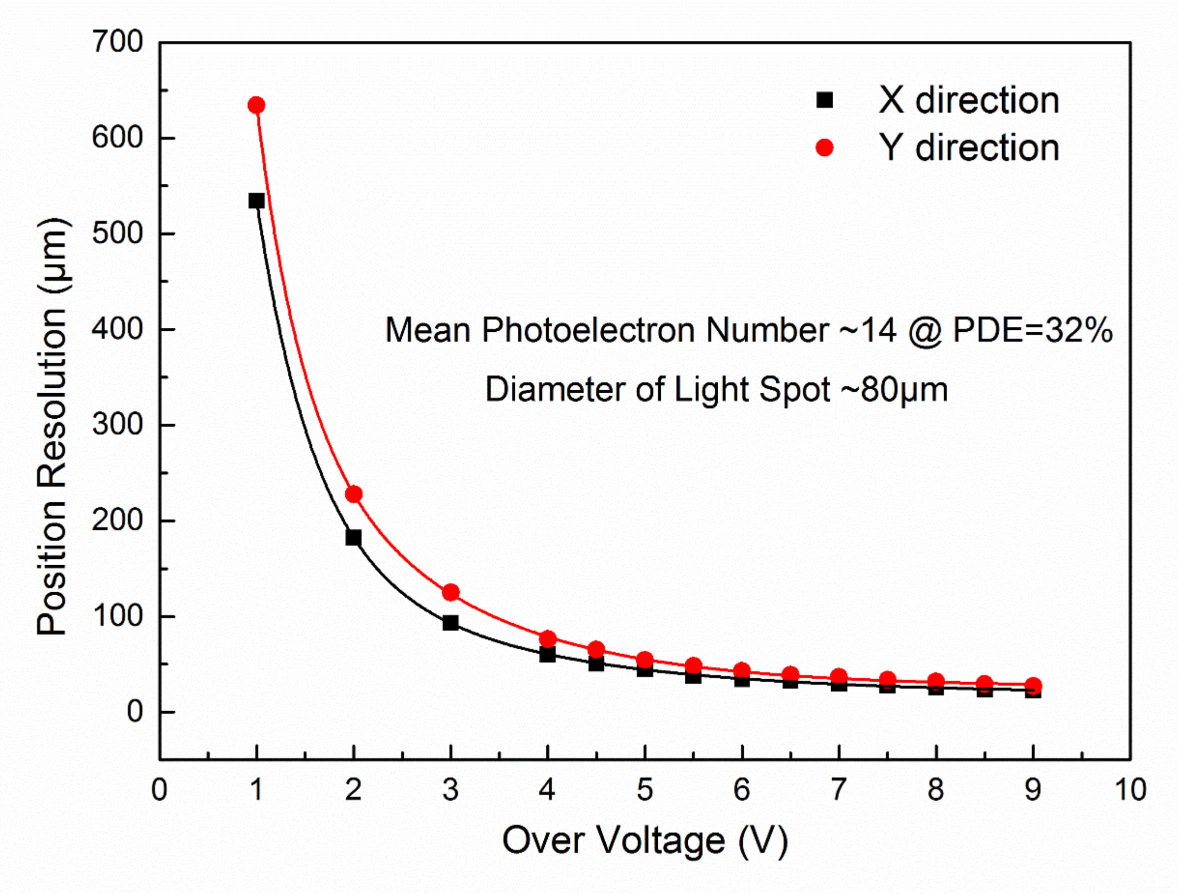
Reconstruction of 13 × 13 incident light spot positions with MPEN ~15 and the diameter of the light spot is ~ 80 μm. $PR_{System\text{-}X}$=34.9±10.3 μm, $PR_{System\text{-}Y}$=40.1±12.7 μm



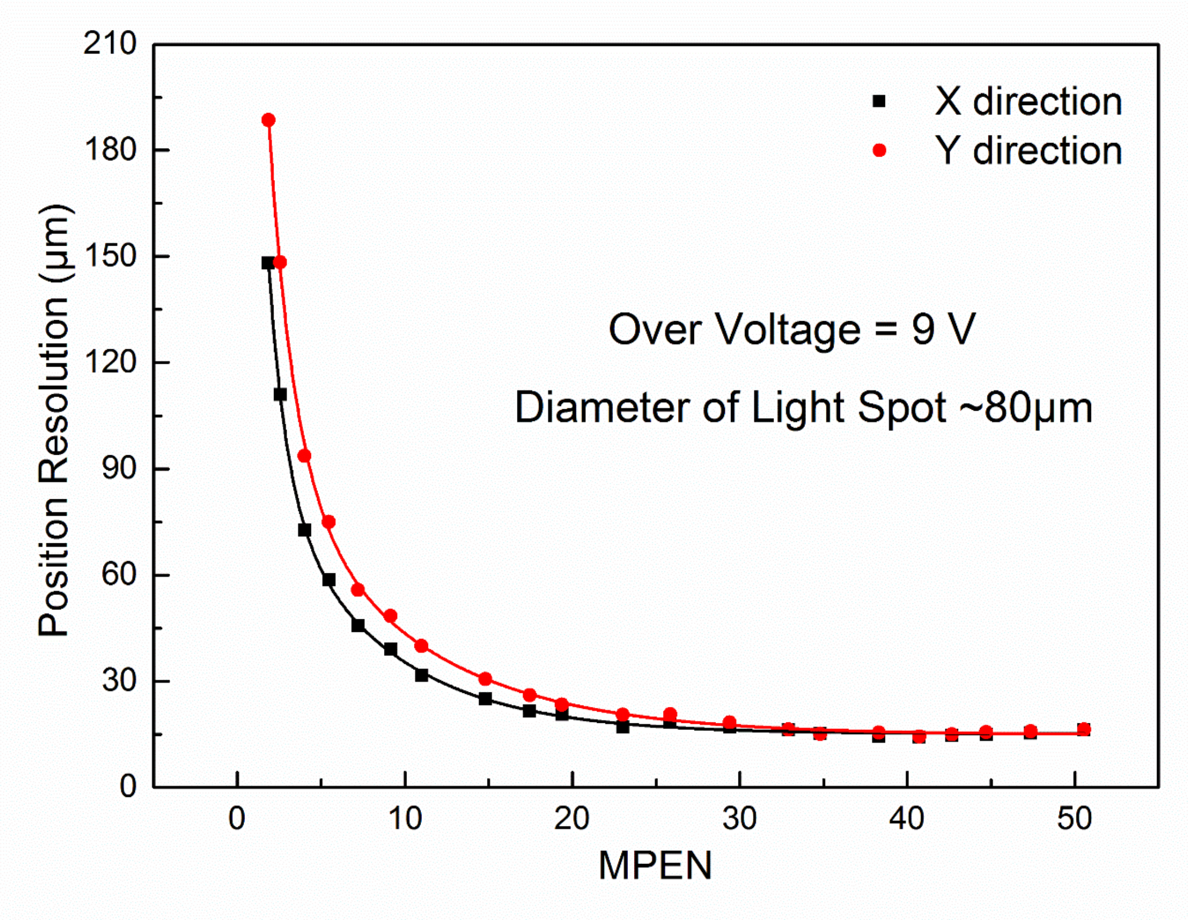


The position resolution of the measurement system in X, Y direction at (0, 0)

Results—Position Resolution

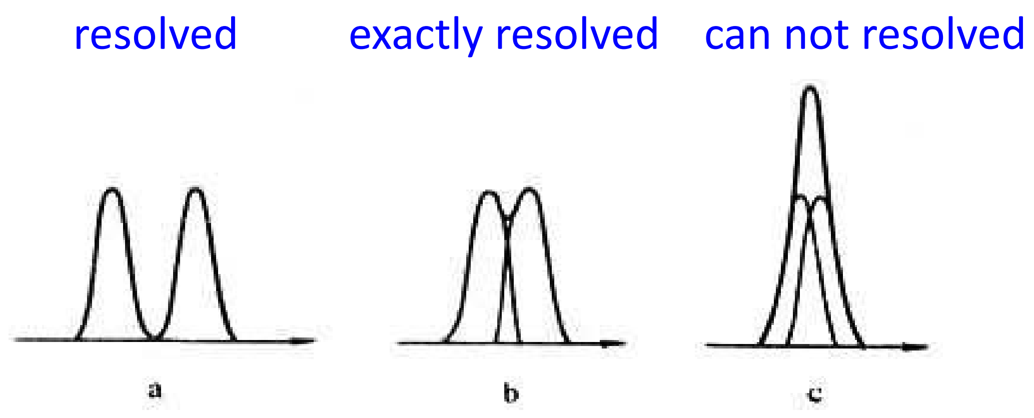


Dependence of the position resolution of the measurement system on the over voltage at the position (0,0)

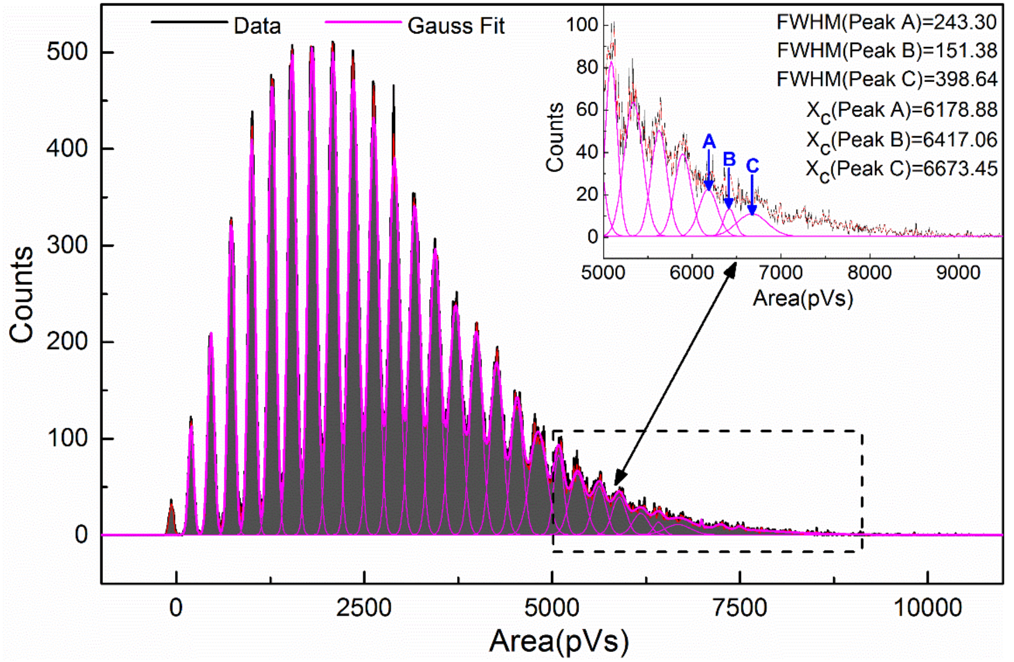


Dependence of position resolutions of the measurement system on MPEN at the position (0, 0)

Results-- Photoelectron Number Resolution



FWHM(Peak A)=243.30 pVs Xc(Peak A)=6178.88 pVs
FWHM(Peak B)=151.38 pVs Xc(Peak B)=6417.06 pVs
FWHM(Peak C)=398.64 pVs Xc(Peak C)=6673.45 pVs



Pulse area distribution of the summed signal from 4 cathodes

resolved : $\Delta X_{AB} = |X_C(\text{Peak A}) - X_C(\text{Peak B})| = 238.18\,pVs > \frac{FWHM(\text{Peak A})+\text{FWHM(Peak B)}}{2} = 197.34\,pVs$

can not resolved : $\Delta X_{BC} = |X_C(\text{Peak B}) - X_C(\text{Peak C})| = 256.39\,pVs < \frac{FWHM(\text{Peak B})+\text{FWHM(Peak C)}}{2} = 275.01\,pVs$

The most photoelectron number that can be resolved by CRL-SiPM is ~24 in this work.

Conclusion

- Characterization techniques for Position Measurement Error, Position Resolution and Photoelectron Number Discrimination of PS-SiPM are verified by taking NDL CRL-SiPM as an example.
- The PME of CRL-SiPM with area of 3000 μm × 3000 μm is derived to be 45.4±24.4 μm.
- Excellent position resolution is demonstrated with only a few readout channels (4 cathodes and 1 anode in CRL-SiPM), the X and Y position resolution of the measurement system at (0, 0) is 26 μm and 28 μm respectively when MPEN is ~ 15.
- The Photoelectron Number Resolution of CRL-SiPM is 24.
- CRL-SiPM may find applications in ultra-high resolving scintillation imaging.

Thank you for your attention!

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