SURVEY REPORT · 3 Aug 2026

SiPM Selection investigation for the CEPC Endcap Aerogel RICH

Haojie Dong · CEPC Cherenkov Detector Group · Internal discussion, 3 August 2026

Content

Why SiPM?

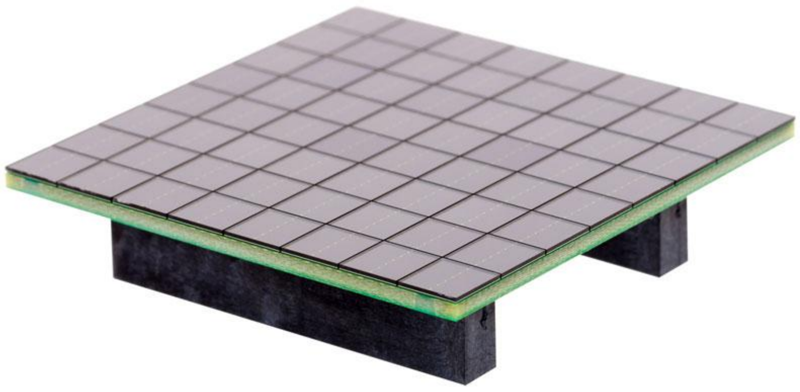
SiPM has been chosen as the baseline photodetector for the CEPC endcap RICH

Magnetic field immunity — insensitive to the 3 T solenoid field, where PMTs / MaPMTs cannot operate and MCP-PMTs suffer orientation-dependent gain loss

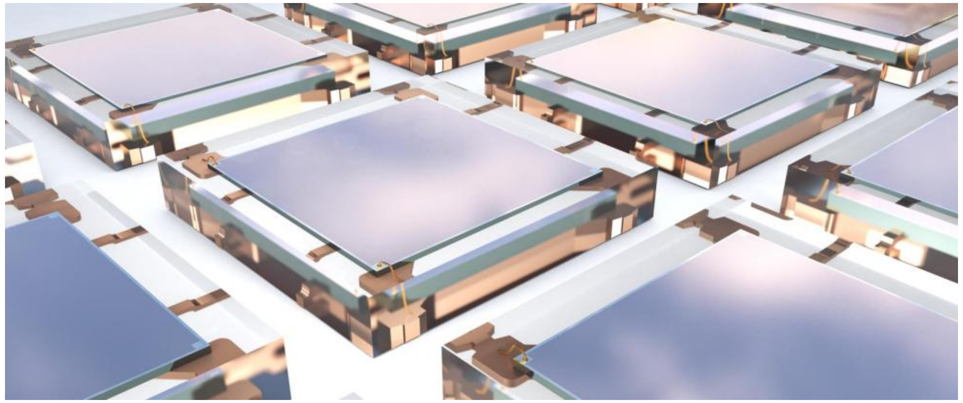
High photon detection efficiency — PDE of 40–63% at 420 nm (vs. ~20% QE for MaPMTs), critical for aerogel radiators yielding < 10 photons/cm

Compact & granular — mm-level pixels, few-mm thickness, low material budget, low-voltage operation (25–53 V)

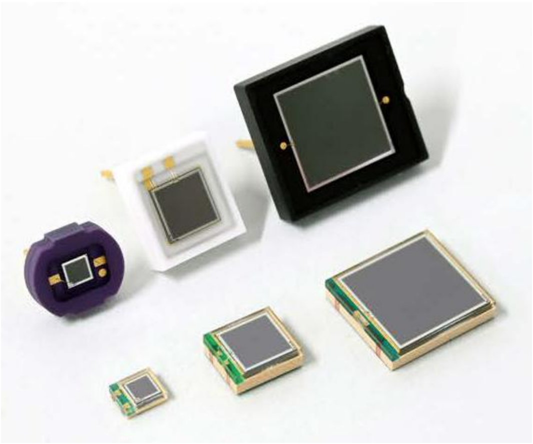
High dark count rate — 100-200kHz/mm^2@room temperature, become much noisier after heavy irradiation.



8×8 SiPM array (3 mm ch., four-side tileable)



SiPM chips in wafer-level packaging



Single SiPM sensors in various packages (ceramic / SMD / TO), 1.3–6 mm active area.

Preliminary specifications of SiPM

Baseline requirements for the photodetector — used as selection criteria throughout this survey.

Parameters	Values	Comments
Spectral response range	>300 nm	to get more photoelectrons
Photon detection efficiency	Peak value ~50%	
Spatial resolution	~300 μm	better angular resolution then better PID performance
Single SiPM size	$1 \times 1 mm^2$ (one readout for each SiPM); or $3 \times 3 mm^2$ or $6 \times 6 mm^2$ (with charge sharing readout)	position sensitive SiPM (for 3x3 or 6x6 mm^2) is an option
Time resolution	100-200 ps	to have short readout time window
Dark noise rate	100 – 200 kHz @ room temperature	acceptable if keep unchanged
Radiation tolerance	10^{12} - 10^{13} $N_{eq.}$ /cm^2	to be further studied
Working conditions	cool down to -20℃ ? regular annealing needed?	to be further studied
Crosstalk	a few percent (1-5%) ?	Keep it low for compact arrange and large size
Total area	~1.6 m^2	an initial calculation

from Z. Qin, "Investigation of an Endcap Cherenkov Detector for CEPC", Guangzhou, July 15, 2026

SiPM Vendor Overview

Six vendors： Hamamatsu, onsemi, NDL, Broadcom, Joinbon, FBK

Vendor	Country / Region	Highest PDE @420 nm	Size range	DCR class (kHz/mm², typ @RT)	SPTR	Temp. floor	Spectral range(nm)	Crosstalk
Hamamatsu	Japan	~48–50%	1–6 mm	41–167*	70–135 ps (lit.)	−20 / −40 °C	320-900	3-10%
Broadcom	USA / Germany	**63%**	**2–4 mm**	111–270	~66 ps	−40 / −20 °C	300-900	9-34%
onsemi	USA (ex-SensL)	41–50%	1–6 mm	**30–150 (21℃)**	—	−40 °C	300-900	7-25%
NDL	China (BNU)	45–47.8%	1–6.24 mm	**150–650 (20℃)**	—	−20 °C (?)	300-900	—
Joinbon	China (Hubei)	32–35% (+2 V)	1–3 mm	88–288	—	−45 °C	250-950	3-3.5%
FBK	Italy	**60–63%**	1–2 mm (custom)	~100	<50 ps (intrinsic, claim)	< -40℃ (?)	300-900	15-20%

Data sources: most of values are quoted from the official vendor datasheets, some of them from literature or reports, put in backup

- onsemi has the lowest DCR, 30 kHz/mm² typ., Broadcom has the highest PDE, 63% at 420 nm.
- Broadcom and FBK offer no 1 mm device;
- No vendor combines a 1 mm pixel with PDE above 50%.
- onsemi, NDL and Joinbon publish no SPTR, so their timing capability is unverified.
- No vendor publishes radiation tolerance.

Hamamatsu— Largest Market Share

Series-level overview (not an exhaustive model list)

Series	Size options	Cell	PDE @420 nm	DCR (kHz/mm², 25 °C typ)	Gain	Timing (SPTR/CRT)	crosstalk
S13360 (53 V platform, single)	1.3 / 3 / 6 mm	25 / 50 / 75 µm	24–47% (highest at 75 µm)	41–56	1.7–4.0e6 (50/75 µm)	lit. SPTR 70–135 ps FWHM	~10%
S13360-VE / S13361 (TSV arrays)	2 / 3 mm ch., 4×4 / 8×8	50 µm	~37–38%	56–75	1.7e6	lit. SPTR 70–135 ps FWHM	~10%
S13615 (1 mm arrays)	1 mm ch., 4×4 / 8×8 / 16×16	25 / 50 µm	~37% (50 µm type)	90	1.7e6	—	~10%
S14160 / S14161 HS (38 V new platform)	3 / 4 / 6 mm, single + arrays	50 µm	~48%	~167 (from dark current; to confirm)	2.5e6 (+2.7 V)	CRT ~200 ps FWHM (160–270, LFS)	7%
S13552 (strip line)	0.23×1.625 mm ×128 ch	57.5 µm	~45–46%	160	3.0e6	—	~10%

Pros: Best engineering maturity and documentation; TSV tiling: smallest dead zones; Good batch uniformity (array channel Vop spread ≤0.2–0.3 V)

Cons: 1 mm pixels PDE only ~37%

Experiment usage: ePIC dRICH: S13360 3 mm; LHCb SciFi: S13552;

Broadcom

Series-level overview (not an exhaustive model list)

Series	Size	Cell	PDE @420 nm	DCR (kHz/mm²)	Gain	Timing (SPTR)	crosstalk
NUV-MT (flagship)	2×2 mm single / 3.7 mm ×16 array (4×4)	40 µm	63% (+12 V; 420 nm is the peak)	125	7.3e6	66 ps FWHM (DRD4 measured)	23%
NUV-HD (FBK process, mass production)	3 / 3.72 mm	30 µm	43% (+3 V) / 54–55% (+7 V)	111–120 (+3 V) / 255–270 (+7 V)	1.6–3.3e6 (+3/+7 V)	<50 ps intrinsic (MT variant)	9–11% (+3 V) / 29–34% (+7 V)
K-Type (legacy KETEK line)	3 mm ×64	25 µm	—	—	—	—	—

Pros: Only off-the-shelf PDE >60% @420 nm; Best commercial timing performance; 4-side tileable (NUV-HD)
Cons: No 1 mm off-the-shelf device (minimum 2 mm); Crosstalk 23% (NUV-MT) on the high side; Operating ranges: NUV-MT cool-side limited only −20 ° C
Experiment usage: NUV-HD-family devices used in DUNE (FBK NUV-HD-Cryo); NUV-MT is the PET / ToF benchmark; multiple SPTR publications

onsemi

Series-level overview (not an exhaustive model list)

Series	Size	Cell	PDE @420 nm	DCR (kHz/mm², 21 °C)	Gain	Timing	crosstalk
C-Series	1 / 3 / 6 mm	10 / 20 / 35 / 50 µm	41% (1 mm, 35 µm, +5 V) / 47% (3 mm, 50 µm, +5 V)	30 (1 mm — lowest of all vendors) / 33 (3 mm)	3e6 (+2.5 V)	Fast-out rise 300 ps; FWHM 600 ps (1 mm)	7% (35 µm) / 10% (50 µm) (@+2.5 V)
J-Series	3 / 4 / 6 mm	20 / 35 µm	38% (+2.5 V) → 50% (+6 V)	50 → 150(+6v)	2.9–6.3e6 (+2.5/+6 V)	Std-out rise 90–110 ps; fast-out FWHM 1.5 ns	8% → 25% (+2.5 V→+6 V)

Pros: Lowest DCR of all vendors (MicroFC-10035: 30 kHz/mm²); Lowest Vbr temperature drift (21.5 mV/° C); Unique fast-output architecture for timing; −40…+85 ° C

Cons: 1 mm type reaches only 41% PDE; No 1 mm TSV array (;poor tiling fill factor); Note: low DCR at +2.5 V while high PDE needs +5/+6 V (different overvoltage points)

Experiment usage: Early LHCb irradiation studies (up to 10^14 neq); Several mid-scale experiments and space projects

NDL

Series-level overview (not an exhaustive model list)

Series	Size	Cell	PDE @420 nm (= peak)	DCR (kHz/mm², 20 °C)	Gain	Timing (SPTR)	crosstalk
EQR06	3 mm	6 µm	30%	276	8e4	—	—
EQR10	1 / 3 mm	10 µm	32–36%	400–500	1.7–2.0e5	—	—
EQR15	1 / 1.3 / 3 / 6 mm	15 µm	45%	250	4e5	—	—
EQR20	3 / 6 mm	20 µm	47.8%	150 typ / 450 max	8e5	—	—
PSS (position-sensitive)	3 / 6 mm	10 / 20 µm	32% / 40%	650 / 150	2e5 / 8e5	—	—

Pros: True 1 mm off-the-shelf devices; EQR structure: no surface resistors → fill factor kept even at small cells; PSS: unique position-sensitive route (large channel-count reduction)

Cons: Lower gain (~10^5) — demanding on front-end electronics; DCR on the high side; No public SPTR / irradiation / crosstalk data (to be requested); Test conditions at 20 ° C

Experiment usage: PSS listed by the BINP FARICH paper as a sub-mm-resolution candidate

Joinbon

Series-level overview (not an exhaustive model list)

Series	Size	Cell	PDE @420 nm (= peak)	DCR (kHz/mm², 25 °C)	Gain	Timing	crosstalk
TN1000	1 mm	37 / 50 µm	32–35% (note: quoted at +2 V; high-overvoltage data not published)	110–120 typ / ~200–287 max	3.8e6	—	2.5% / 3.5% （37/50 µm，@+2 V）
TN3000	3 mm	37 / 50 µm	32–35% (+2 V)	88–124	2.7e6	—	1.3% / 3.0% （37/50 µm，@+2 V）
JARY arrays	1 mm ×64 (8×8, 0.2 mm gap) / 3 mm ×64	50 µm	35%	124 / 288 (array-handbook values identical to the 3 mm single — questionable, to confirm with vendor)	2.7e6 (TBC)	—	~3%

Pros: Both 1 mm single devices and arrays available; −45 °C lower limit suits deep-cooling

Cons: PDE quoted only to 35% (+2 V; high-overvoltage curves missing — true ceiling TBD by measurement); No SPTR / irradiation data;

Experiment usage: Currently not found

FBK

No standard off-the-shelf catalogue

NUV-HD

35 μm cell; peak PDE 60–63% @410–420 nm (abstract 63% / text 60%); DCR ~100 kHz/mm²; gain — (custom)

NUV-MT

Microlens; 95% fill factor; intrinsic SPTR <50 ps; LF2 M3 readout 40 ps FWHM [arXiv:2506.11655]; gain ~7.3e6 (Broadcom @+12 V)

NUV-HD-Cryo

Deep-cryogenic version; adopted by DUNE

LG-SiPM

Position-sensitive (linear-graded) variant

Pros: The only channel that could customize ;
Cons: Customisation cycle 1–2 years;
Experiment usage: DUNE photon detection (NUV-HD-Cryo); DarkSide-20k;

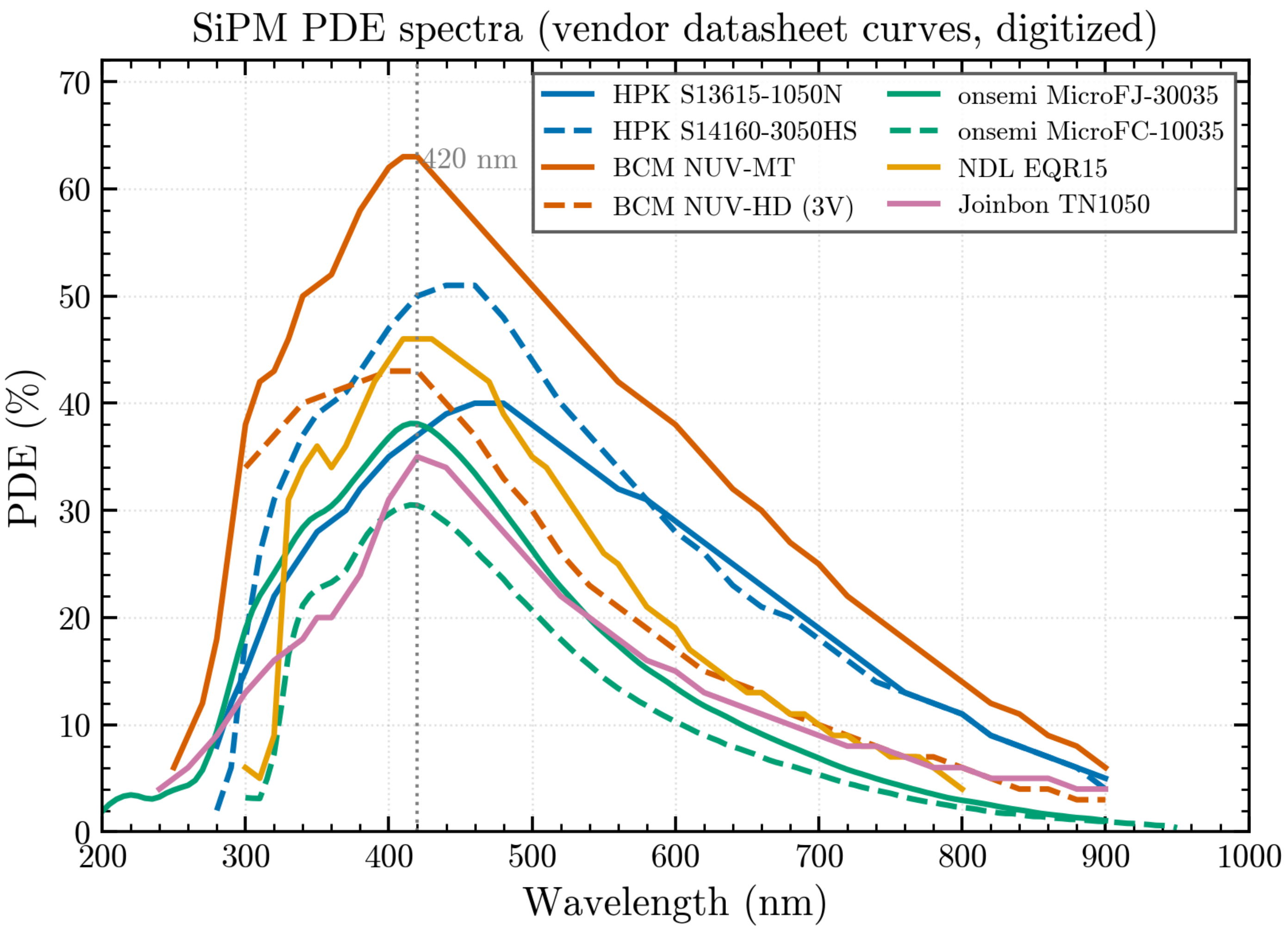
Vendor parameters at peak wavelength, typical values at room temperature

Broadcom/FBK own PDE and timing, onsemi dark rate, NDL 1 mm parts. Nobody quotes radiation.

DEVICE (VENDOR)	AREA / CELL	PDE @peak	DCR PER mm²	GAIN	SPTR (LITERATURE)	crosstalk
S13615-1050N (Hamamatsu)	1.0 mm / 50 µm	40% @450 nm	~90 kHz	1.7×10^6	not published	~10%
S14160-3050HS (Hamamatsu)	3 mm / 50 µm	**50% @450 nm**	167* kHz	2.5×10^6	CRT 160–200 ps	7%
JSP-TN1050-SMT	1mm / 50µm	35% @420 nm	120 kHz	3.8×10^6		3.5%
NUV-MT S4N44P164M (Broadcom)	3.7 mm / 40 µm	**63% @420 nm**	125 kHz	7.3×10^6	**66 ps FWHM**	23% crosstalk
NUV-HD S4N33C013 (Broadcom)	3 mm / 30 µm	43% @420 nm	111 kHz	1.6×10^6	< 50 ps (MT variant)	~17%
MicroFJ-30035 (onsemi)	3 mm / 35 µm	38% @420 nm	50 kHz	2.9×10^6	fast output, 90–250 ps	11%
MicroFC-10035 (onsemi)	**1 mm / 35 µm**	31% @420 nm	**30 kHz**	3×10^6	300 ps rise (fast out)	7%
NUV-MT custom (FBK)	**1–2 mm**	60–63% @420 nm	~100 kHz	7.3×10^6	<50 ps	~23%
EQR15 11-1010D-S (NDL)	**1 mm / 15 µm**	**45% @420 nm**	250 kHz	4.0×10^5	not published	

- All parameters are quoted at each vendor's recommended operating overvoltage
- PDE is taken at its peak wavelength (λp).
- Crosstalk ~ mean estimated (same cell-pitch device or same process), exact value not published.

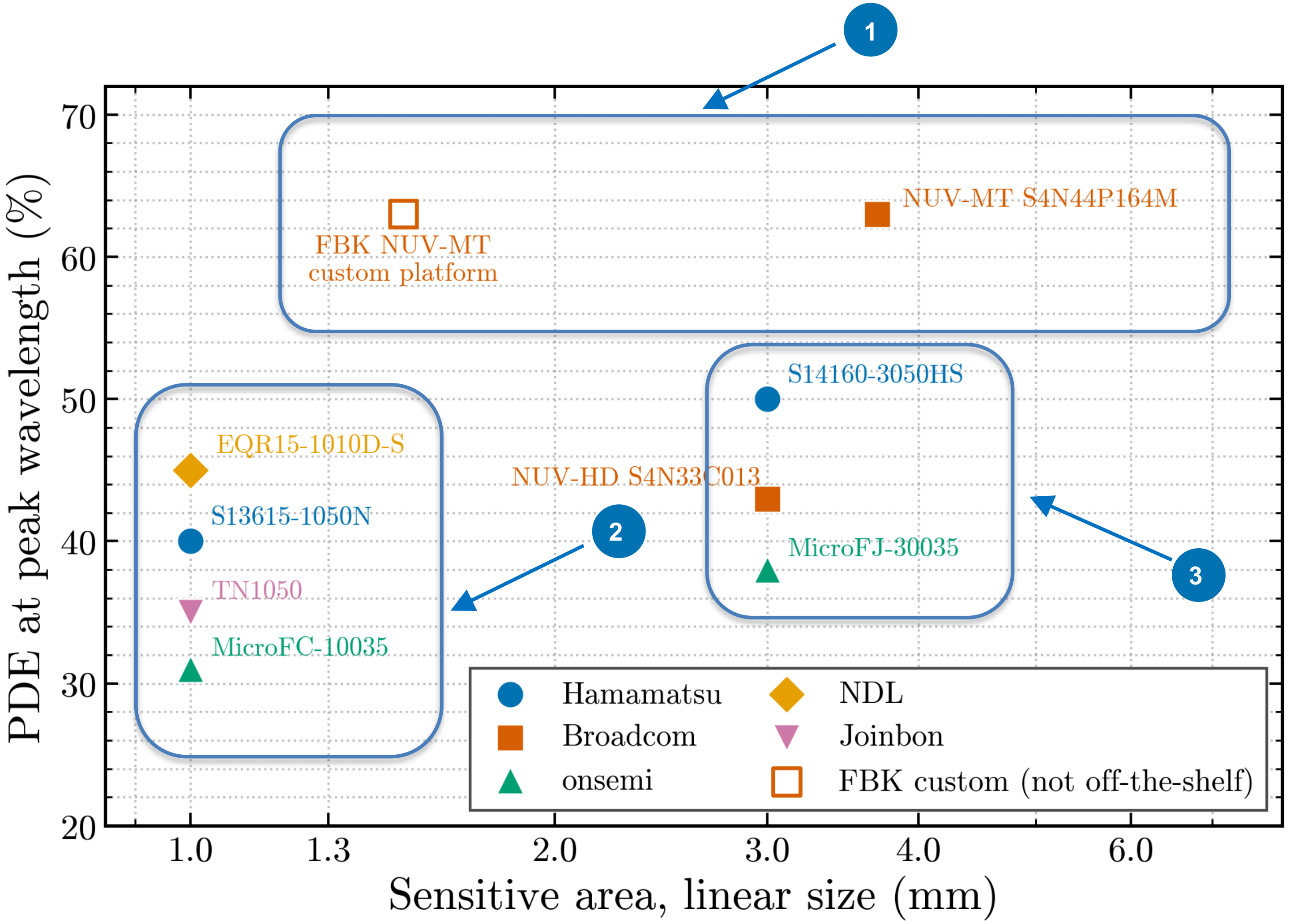
Photon detection efficiency



PDE vs. wavelength data are extracted from official vendor datasheets; details in backup.

- Except HPK, all SiPM PDE peaks lie at ~420 nm.
- All models cover the 300–700 nm wavelength range.
- Four models exceed 40% peak PDE: NUV-MT (63%), S14160-3050HS (50%), EQR15 (45%), NUV-HD +3 V (43%).
- Increasing the overvoltage raises PDE, but crosstalk grows as well.

PDE with Sensitive area



HOW TO READ THE PLANE

1 **High PDE**

FBK NUV-T need custom
S4N44P164M not need
But all have high crosstalk ~23%

2 **1 mm parts**

Cell size 1×1 mm, but PDE not reach 50%
Crosstalk ~7%
EQR15-1010D-S PDE 45%, but DCR 250kHz

3 **3 mm parts**

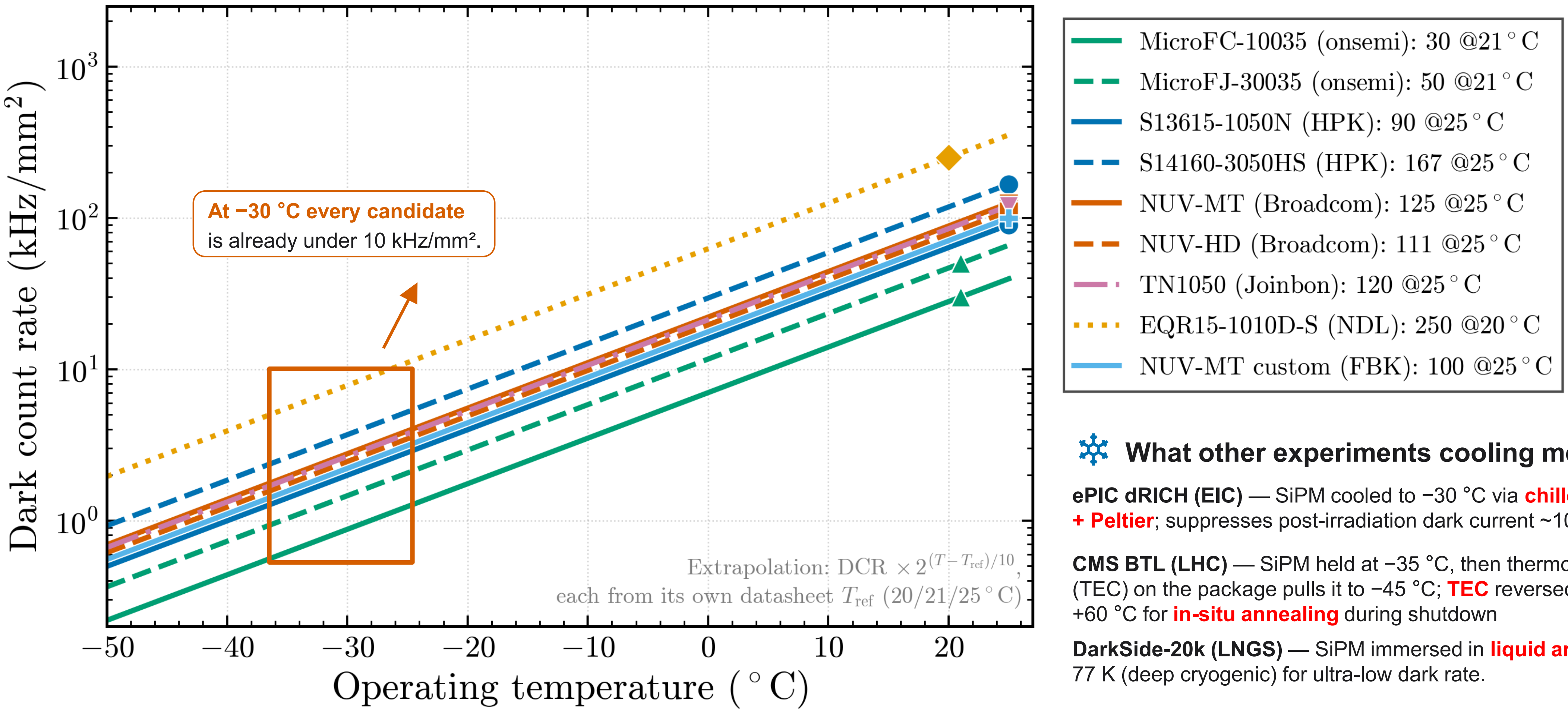
S14160 PDE 50%, DCR 167kHz, crosstalk 7%
S4N33C013 PDE 43%, DCR 111kHz, crosstalk ~17%
FJ-30035 PDE 38%, DCR 50kHz, crosstalk 11%

TSV (Through-Silicon Via)

Vias through the die route the electrode to the back side, keeping the light-sensitive front clean so parts tile seamlessly into a large panel with minimal dead edge. — **To be investigated further**

Dark count rate decide the cooling depth

DCR halves every 10 °C



❄ What other experiments cooling method

ePIC dRICH (EIC) — SiPM cooled to −30 °C via **chilled water + Peltier**; suppresses post-irradiation dark current ~100×

CMS BTL (LHC) — SiPM held at −35 °C, then thermoelectric (TEC) on the package pulls it to −45 °C; **TEC** reversed heats to +60 °C for **in-situ annealing** during shutdown

DarkSide-20k (LNGS) — SiPM immersed in **liquid argon** at 77 K (deep cryogenic) for ultra-low dark rate.

Performance change after radiation

- Hamamatsu: S13360 series, 25/50/75 µm; S14160-3010PS
  - DCR scales linearly with fluence: −30°C: 500 Hz/mm² → 2 MHz @10^{11} → 20 MHz @10^{12} → ~200 MHz @10^{13}； Vbd shifts +1.3–1.8 V @10^{14}
  - After annealing: 175 ° C / 600 h reduces DCR by 1–2 orders
- SensL / onsemi: MicroFC-10020/10050; MicroFJ-60035
  - same linear DCR growth, but ~1 order of magnitude worse than HPK at 77 K (~1 MHz/mm² @10^{14}); advantage: no Vbd shift
  - After annealing: in-situ current annealing (0.8 A) → dark current down to 8–14%

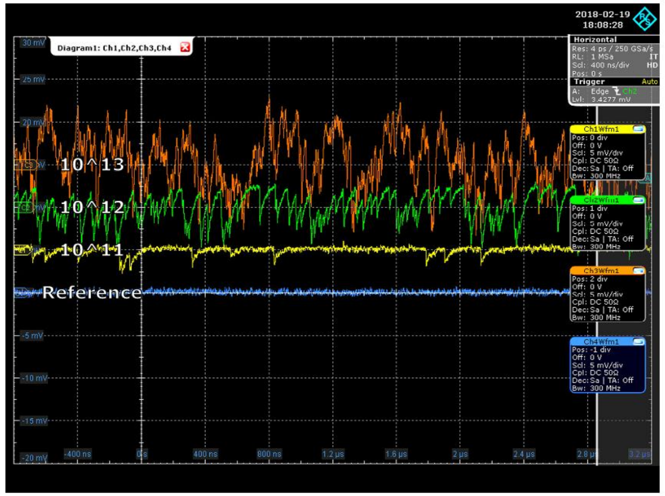


Fig. 8. Dark counts at −30 °C of a Hamamatsu S13360-1350CS SiPMs biased at 51 V: non irradiated (blue) and irradiated up to 10^{11} (yellow), 10^{12} (green) and 10^{13} (orange) n_{eq}/cm^2. The horizontal scale is 400 ns/div.

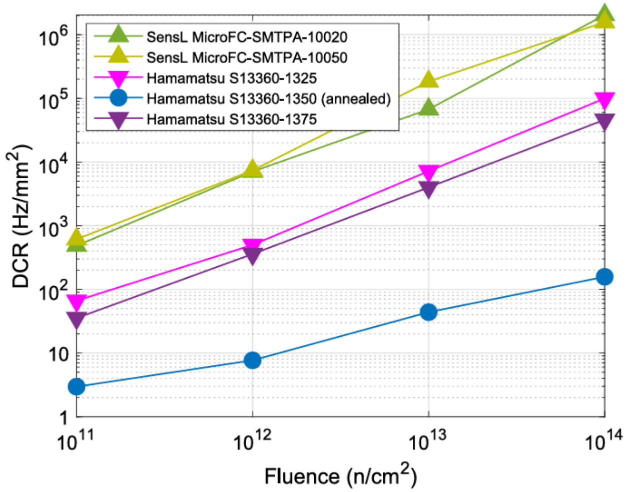
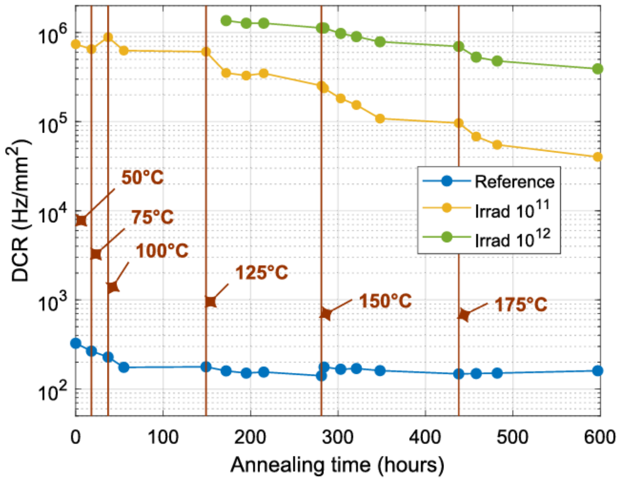


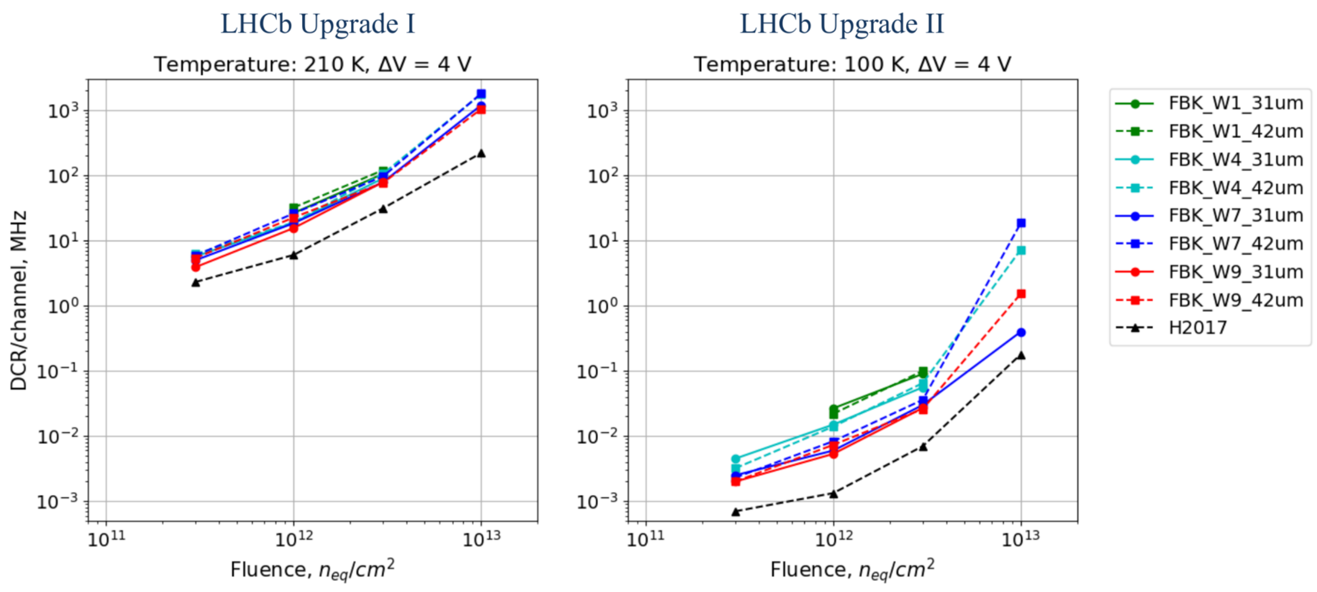
Fig. 12. DCR at 77 K versus neutron fluence for all irradiated devices.



Refs: Calvi et al., NIM A 922 (2019); Gu et al., NIM A 1053 (2023)

Performance change after radiation

- FBK: FBK-2022 31/42 µm modules; NUV-HD
  - Also linearly with fluence, after ~10^{13} super-linear
  - 80 ℃ has no effect; needs ≥135 ° C
- NDL: EQR15 3030D-S
  - dark current ×40 @10^{10} after irradiation
  - After annealing: in-situ 0.8 A / 150 s → down to 0.9%, good recovery



Currás Rivera, PD24 (2024); Merzi et al., Sensors 24 (2024)

1. Irradiation mainly kills you with noise: DCR ∝ fluence;
2. Ranking (77–100 K): **HPK ≥ FBK legacy (H2017) > FBK 2022 ≈ SensL** (~10× worse)
3. −30 ℃ is not enough at 10^{13} (~200 MHz/mm²); need **deep cooling ≤100 K + periodic annealing at 150–175 ° C** (1–2 orders of recovery)
4. Empirical rule: **smaller pixels / lower gain / lower overvoltage are more radiation tolerant**

Candidate shortlist

Device (vendor)	Size / cell	PDE @ peak	DCR @ RT	Crosstalk	Timing	Temp. floor	Reason
S14161-3050HS (Hamamatsu)	3 mm ch., 4×4 / 8×8 TSV, 50 µm	50% @450 nm	~167 kHz/mm²	7%	SPTR 70–135 ps (lit.)	−40 ° C	Best PDE-vs-crosstalk compromise on the market; best documented radiation + annealing behaviour;
MicroFJ-30035 (onsemi)	3 mm single, 35 µm	38% @420 nm	50 kHz/mm²	11%	not published	−40 ° C	Low dark rate and low-voltage platform; 3 mm device with −40 ° C operation; useful comparison point for dark-noise and cooling studies.
EQR15 11-1010D-S (NDL)	1 mm, 15 µm	45% @420 nm	250kHz/mm²	–	–	−40 ° C	Highest PDE among 1 mm candidates at 420 nm; directly meets the ~300 µm spatial-resolution requirement by pixel size; domestic supply and customisation channel.

Discussion and Conclusion

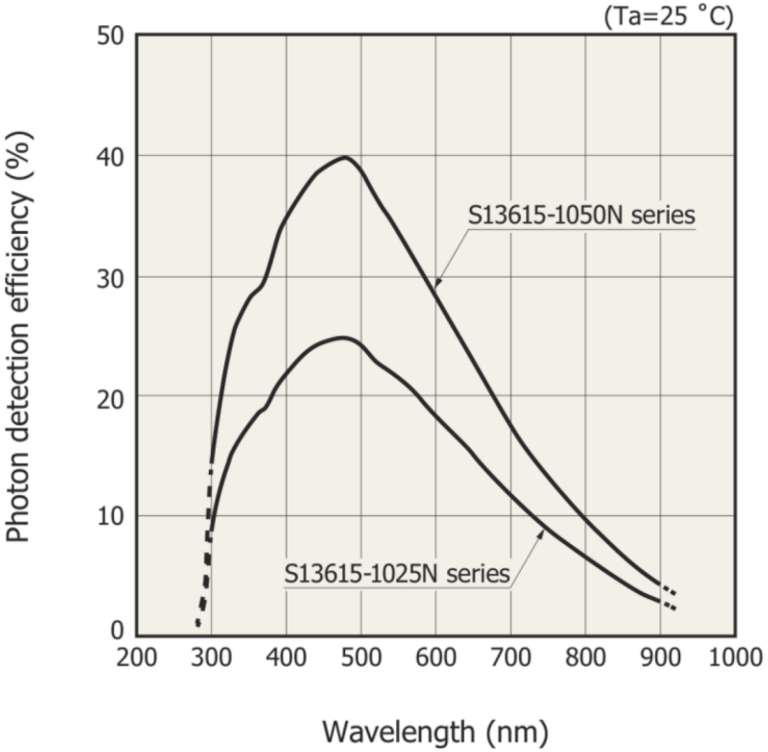
1. Investigated six SiPM vendors based on the preliminary spec.
2. Two conflicts : 1 mm pixel + PDE > 50% cannot found, and neither can PDE ~50% + crosstalk 1–5%.
3. Three candidates proposed: HPK S14161-3050HS · MicroFJ-30035 (onsemi)· EQR15 11-1010D-S (NDL)
4. −30 °C puts every candidate under 10 kHz/mm^2; radiation is main influence of DCR.
5. Next: post-irradiation behaviour need more study—a dedicated study, and real PDE curves + digitisation in the simulation.

Backup

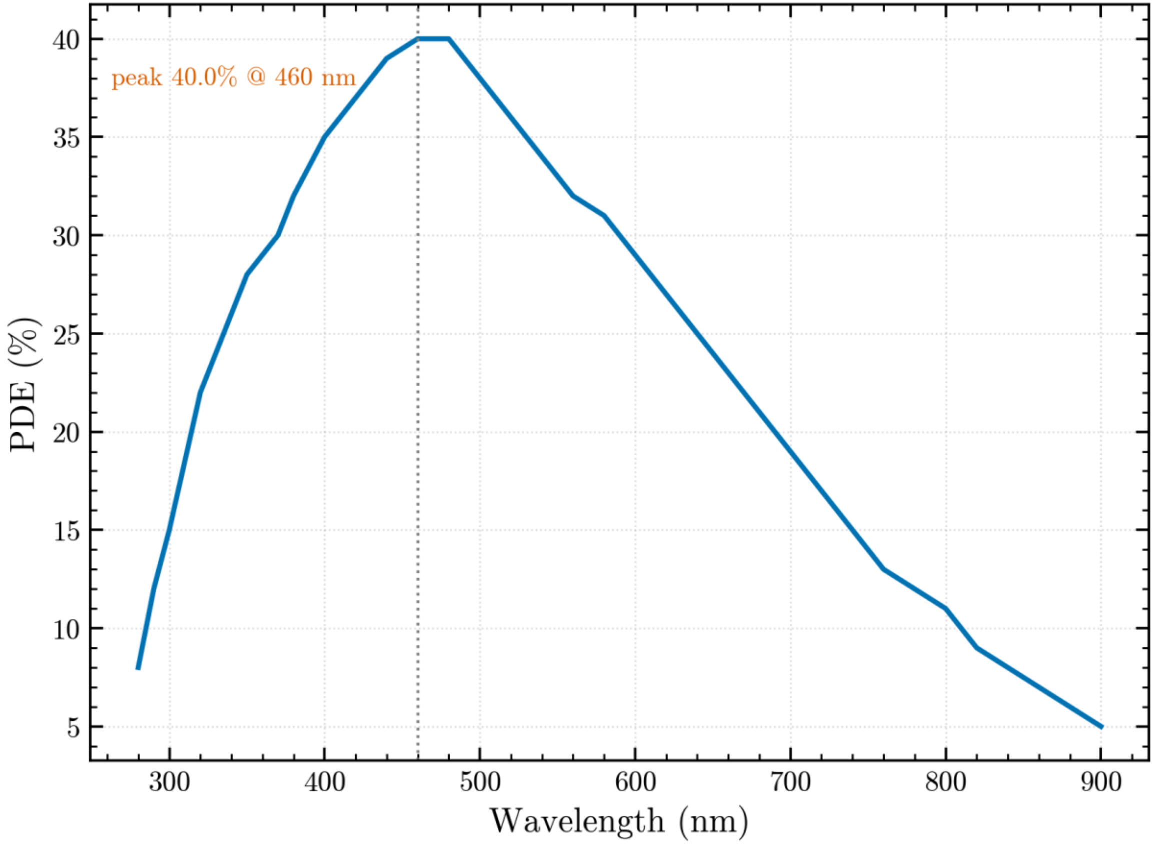
- Values taken from the literature or reports: Hamamatsu S13360 SPTR 70–135 ps — Gundacker et al. (2020) and the CERN DRD4 SPTR measurements (not given in the datasheet);
- Broadcom NUV-MT SPTR ~66 ps —measurement (datasheet states "excellent SPTR");
- FBK SPTR <50 ps —(from arXiv:2506.11655);
- FBK platform PDE/DCR — Gola et al., Sensors 2019, 19, 308;
- Hamamatsu S14161 DCR ~167 kHz/mm² —from the datasheet dark current (0.6 µA typ.), to be confirmed;
- onsemi, NDL and Joinbon publish no SPTR (datasheets quote rise-time only).

$$\mathrm{DCR}\ [\mathrm{kHz/mm^2}] = \frac{\mathrm{CountRate}\ [\mathrm{kcps}]}{\mathrm{ActiveArea}\ [\mathrm{mm^2}]} = \frac{\mathrm{DarkCurrent}\ [\mathrm{A}]}{\mathrm{Gain} \cdot \mathrm{e} \cdot \mathrm{ActiveArea}\ [\mathrm{mm^2}]}$$

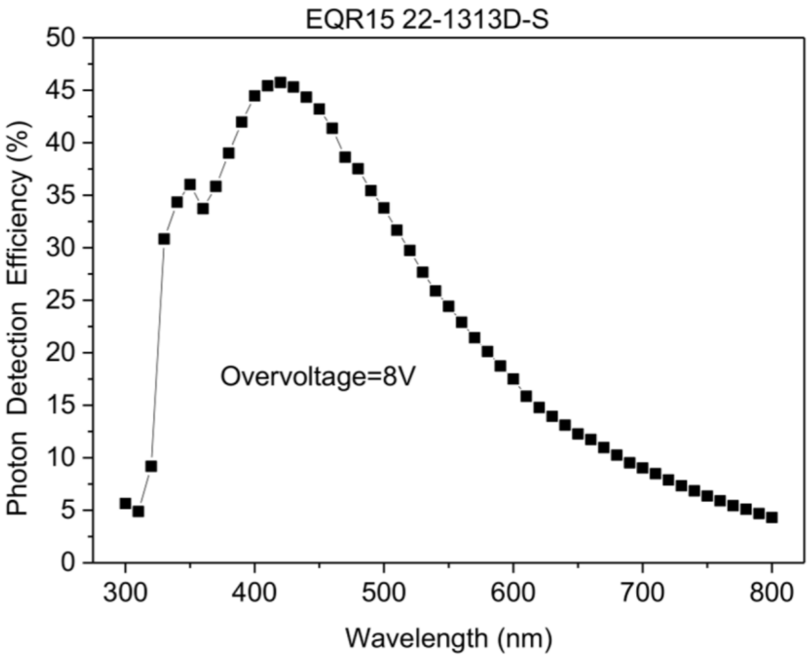
s13615-1050N caption:



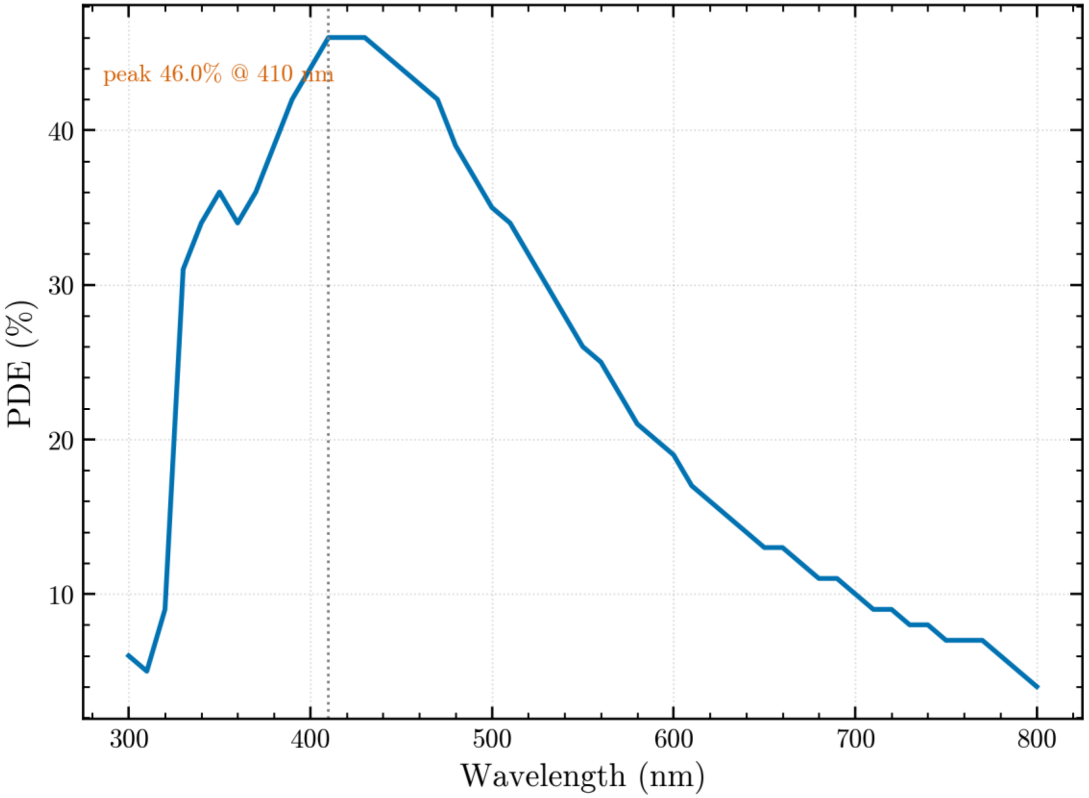
s13615-1050N - digitized (OV 1050N)



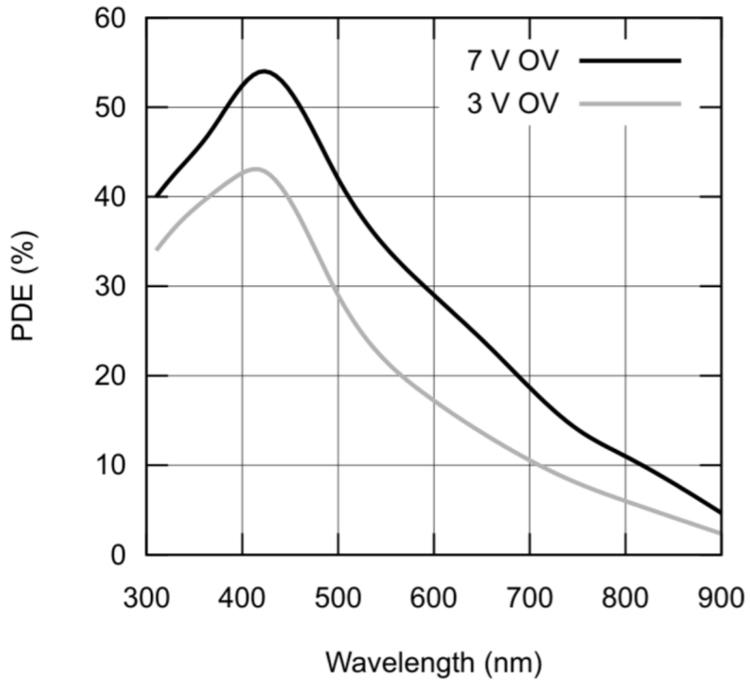
eqr15 caption:



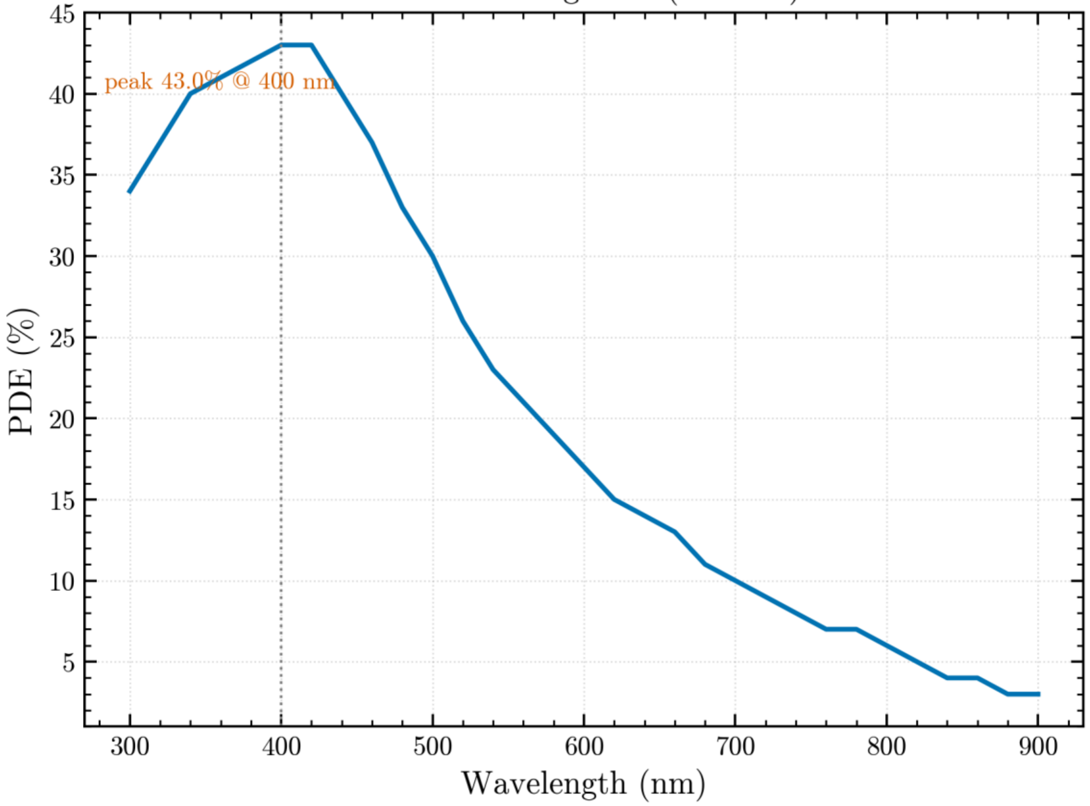
eqr15 - digitized (OV EQR15)



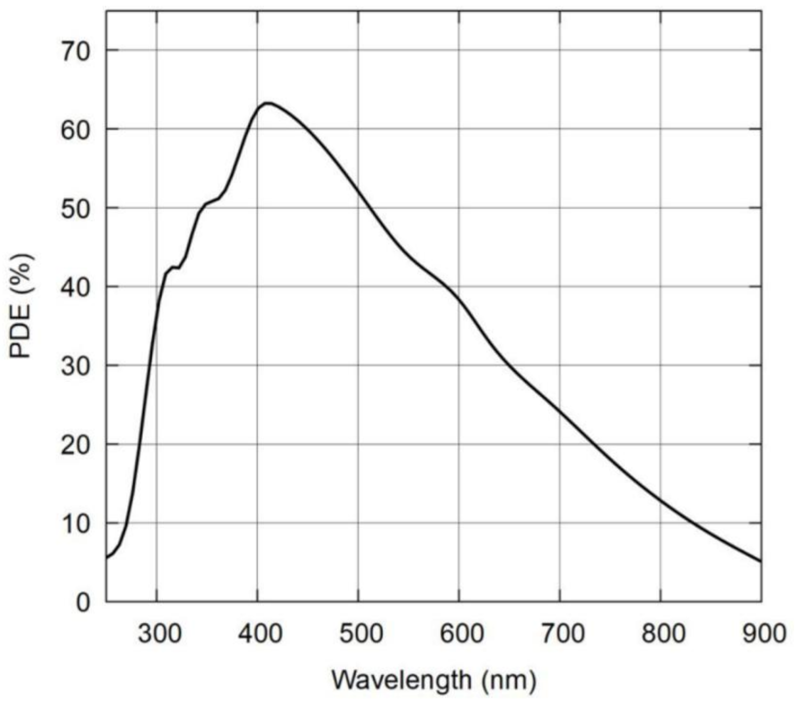
nuvhd-3V caption:



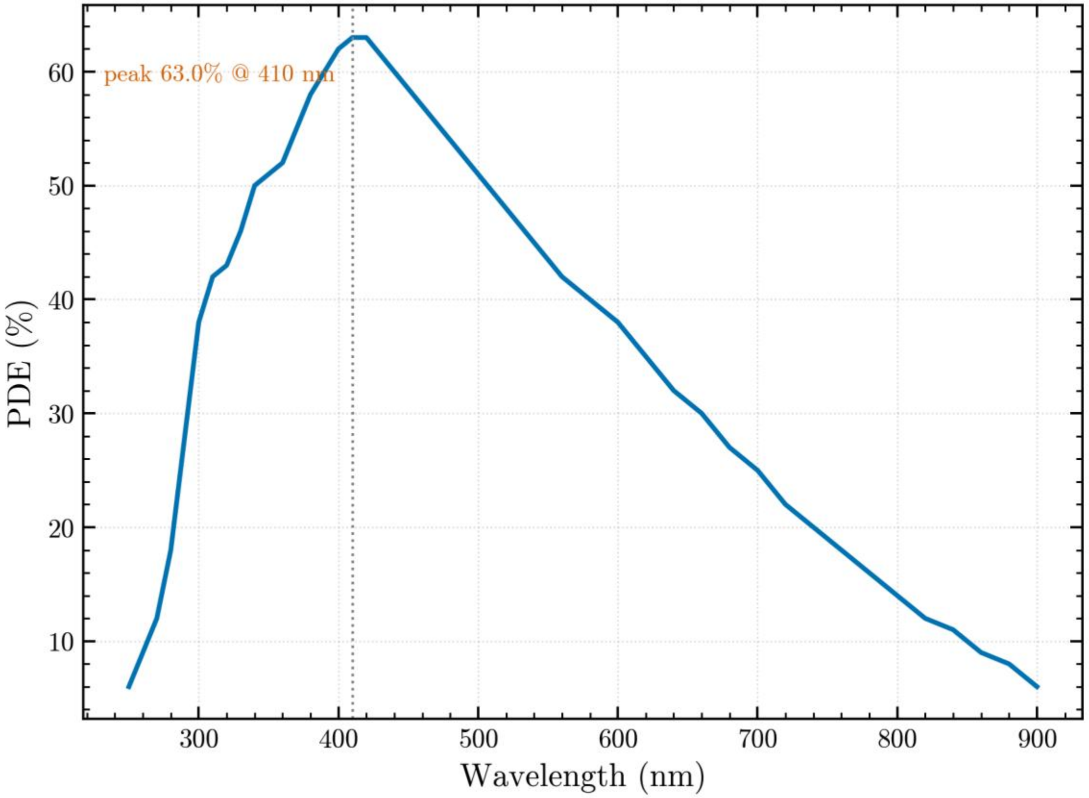
nuvhd-3V - digitized (OV 3 V)



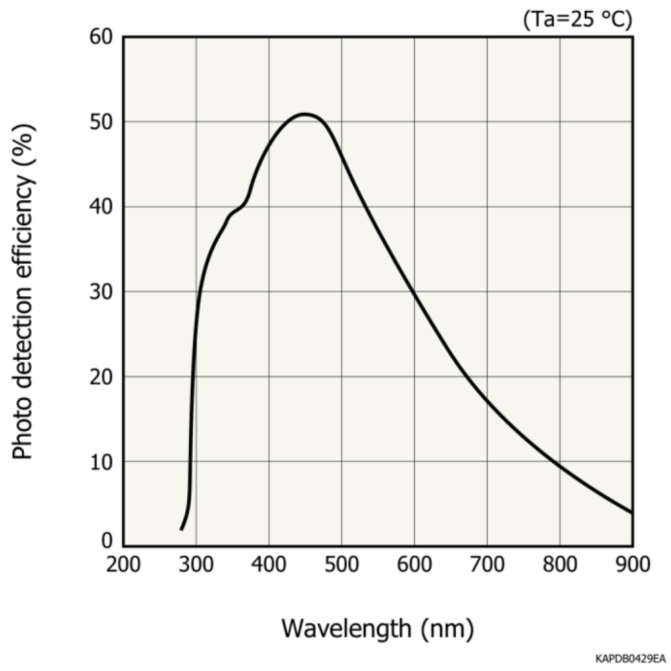
nuvmt caption:



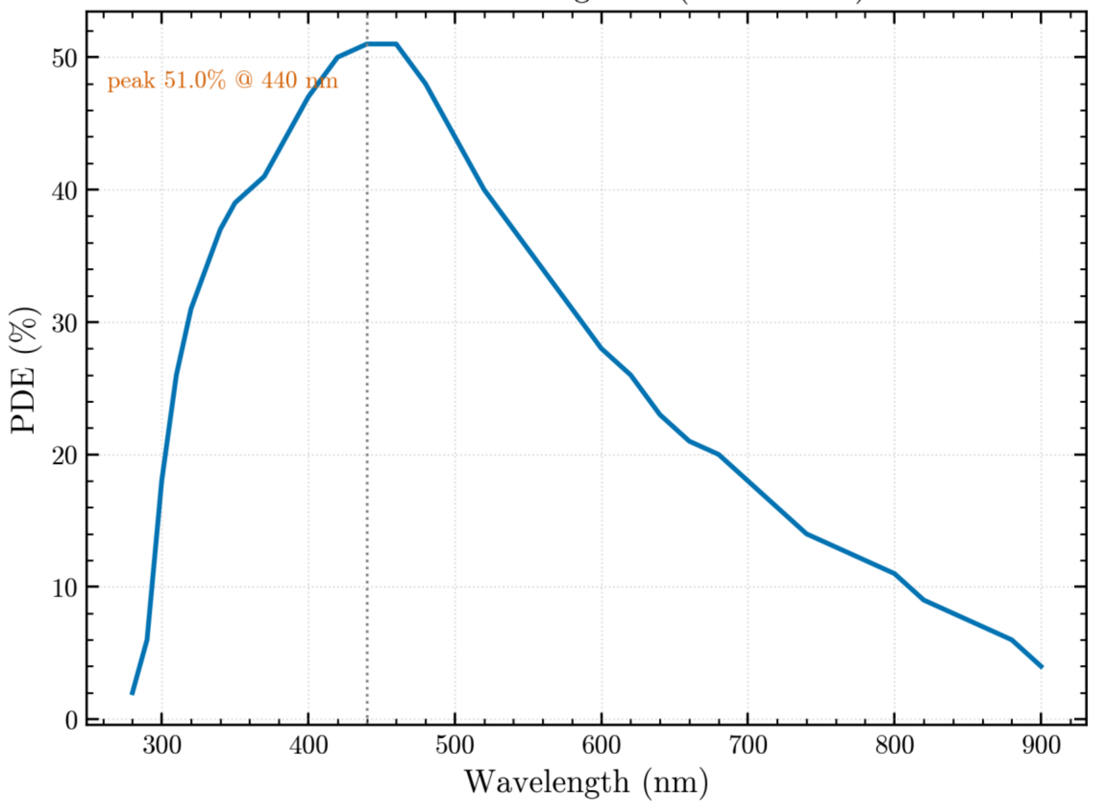
nuvmt - digitized (OV NUV-MT)



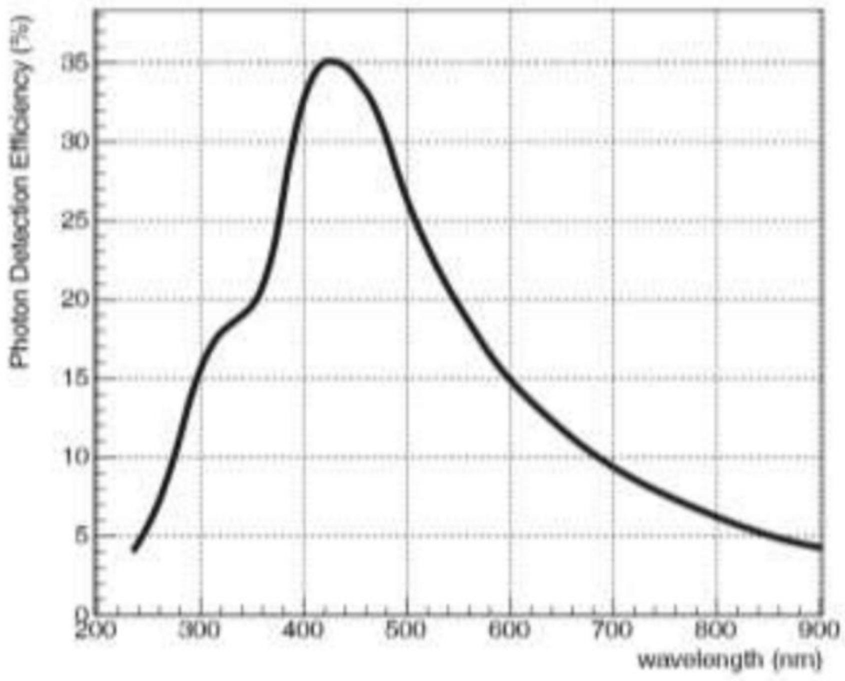
s14160-3050HS caption:



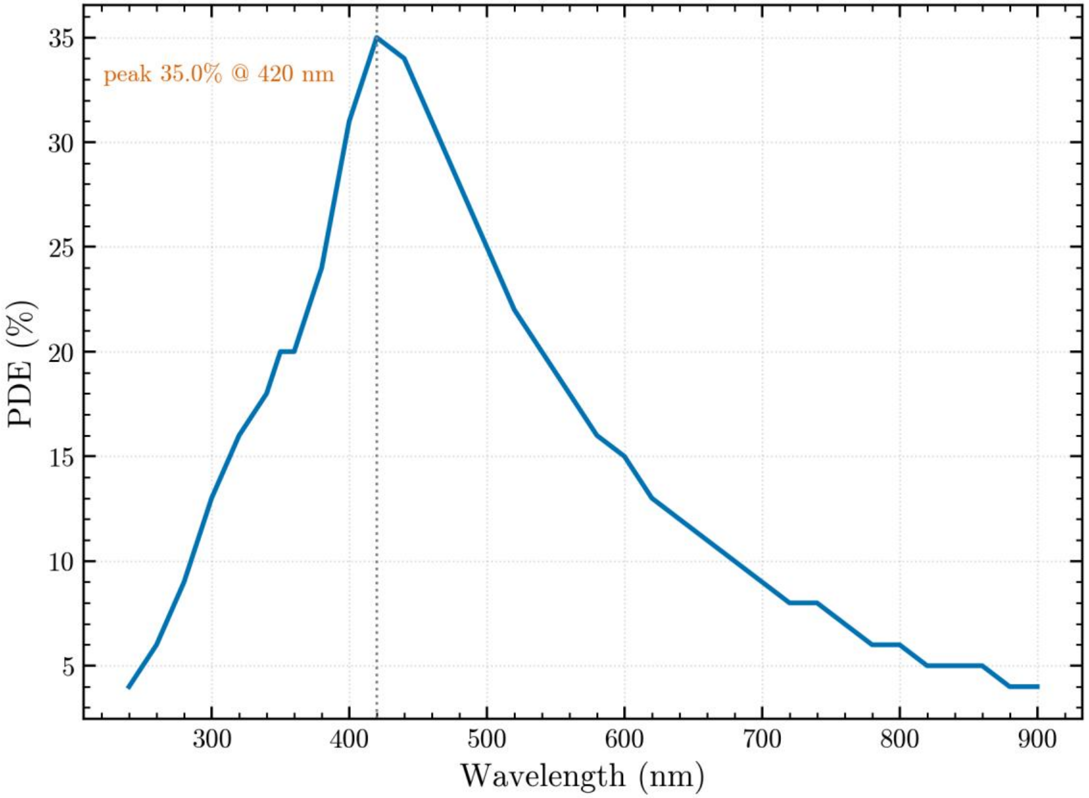
s14160-3050HS - digitized (OV 3050HS)

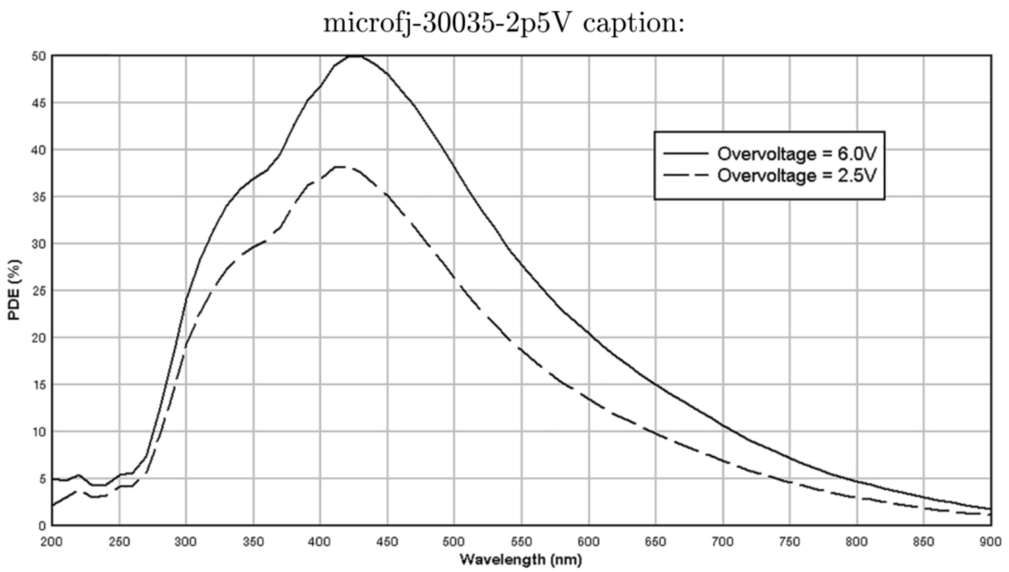


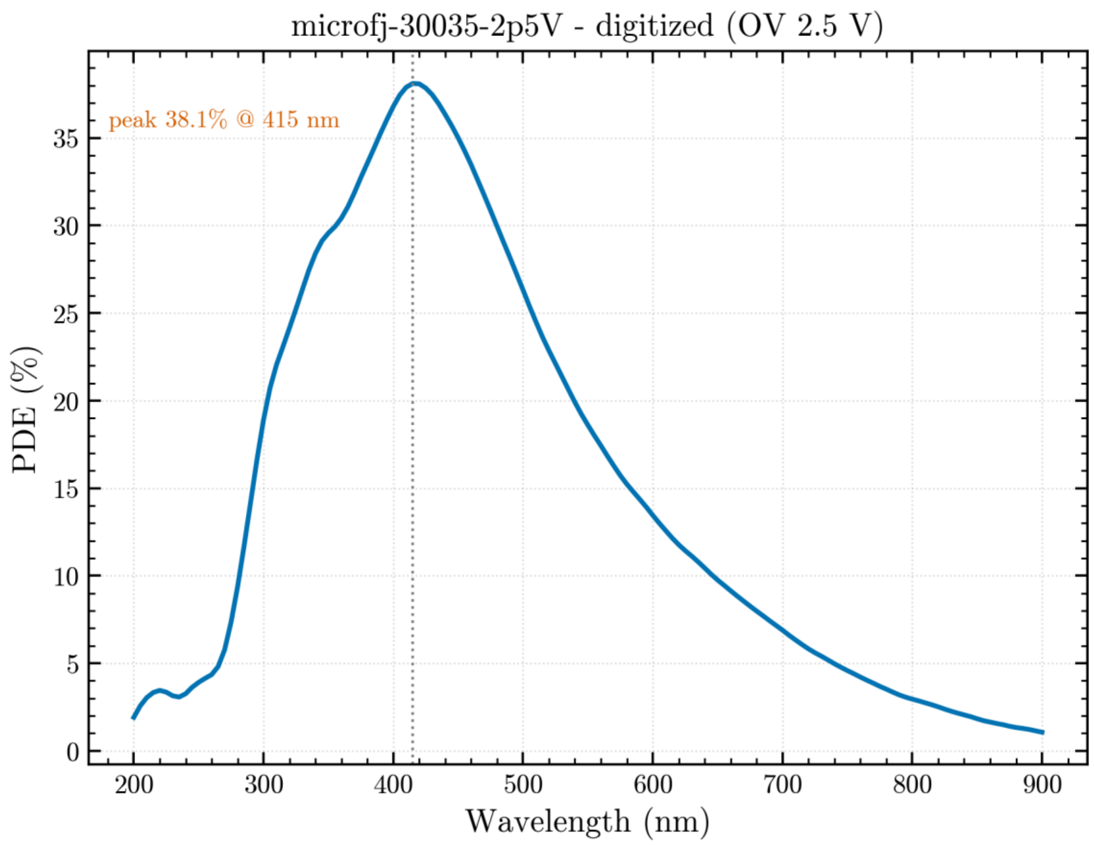
tn1050 caption:



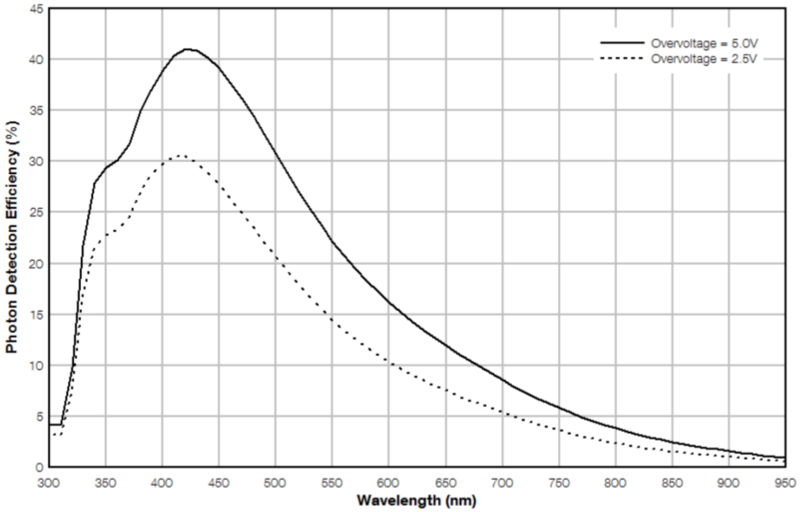
tn1050 - digitized (OV TN1050)




microfj-30035-2p5V caption:
PDE (%)
Wavelength (nm)
Overvoltage = 6.0V
Overvoltage = 2.5V
0
5
10
15
20
25
30
35
40
45
50
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900


microfj-30035-2p5V - digitized (OV 2.5 V)
peak 38.1% @ 415 nm
PDE (%)
Wavelength (nm)
0
5
10
15
20
25
30
35
200
300
400
500
600
700
800
900

microfc-10035-2p5V caption:



microfc-10035-2p5V - digitized (OV 2.5 V)