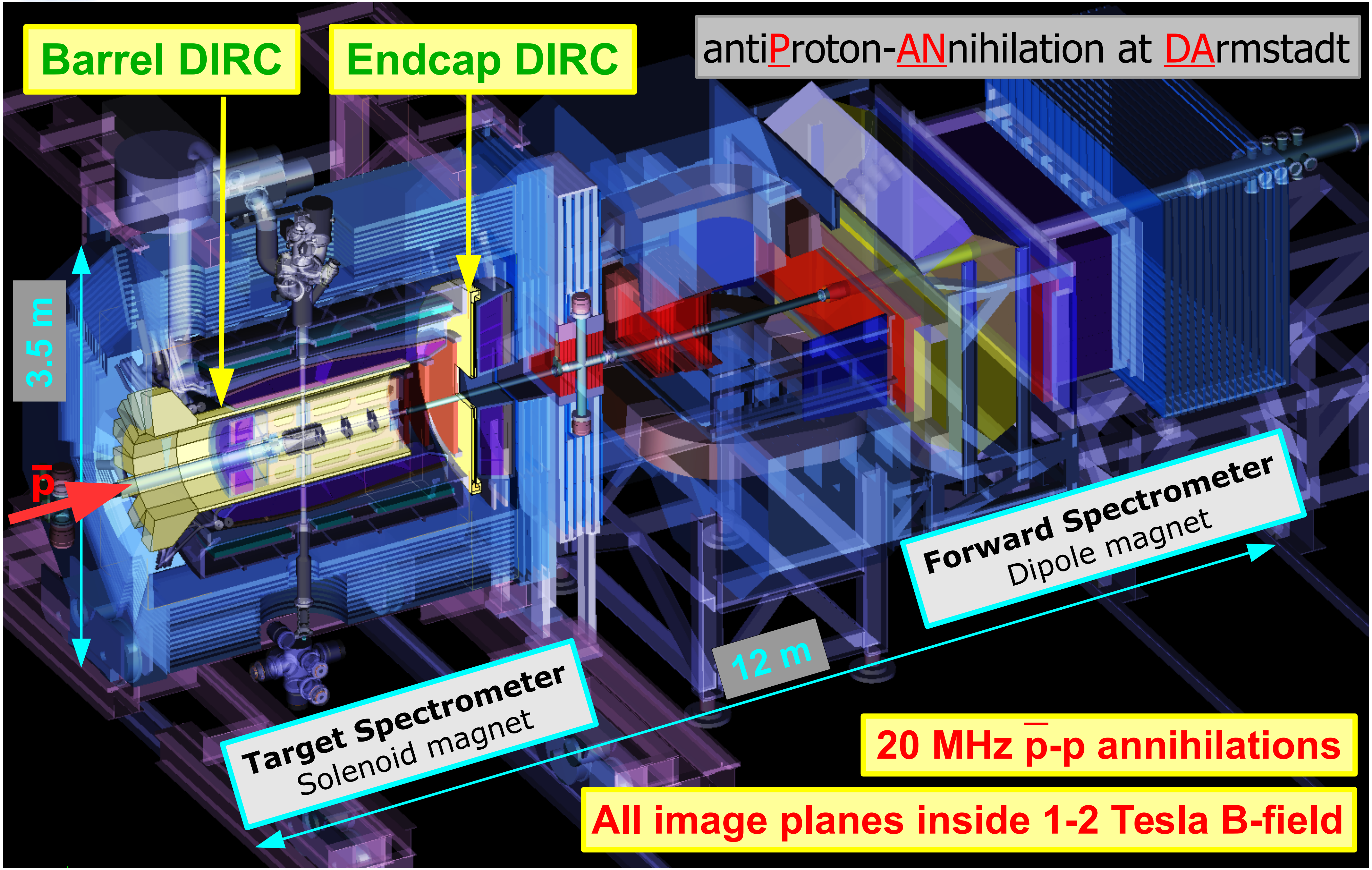
Lifetime of MCP-PMTs and other Performance Features

Albert Lehmann,
M. Böhm, R. Frytz, D. Miehling, M. Pfaffinger, S. Stelter
(University Erlangen-Nuremberg, Germany)

- Introduction and motivation
- Lifetime results with ALD MCP-PMTs
- Information obtainable with TRB scans
- Some properties of new MCP-PMTs
- Outlook and summary

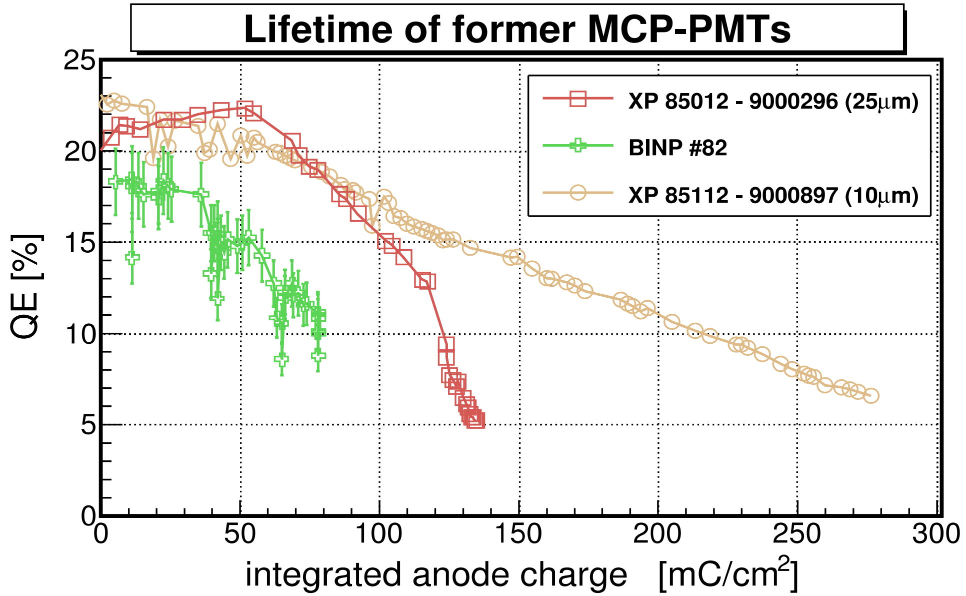
$\overline{\text{P}}$ANDA Detector at FAIR



MCP-PMTs for PANDA DIRCs

- MCP-PMTs are the only suitable sensors for PANDA
  - Compact and available as multi-anode devices
  - Single photon detection even in B-fields of 1 – 2 Tesla
  - Excellent time resolution <50 ps
  - Low dark count rates
- Barrel DIRC
  - Photon rate: ~200 kHz/cm^2
  - **10 years anode charge: 5 C/cm^2**
  - Pixel size: ~ 6 x 6 mm^2
- Endcap DIRC
  - Photon rate: up to 1 MHz/cm^2
  - **10 years anode charge: >5 C/cm^2**
  - **Pixel size: ~ 0.5 x 16 mm^2**

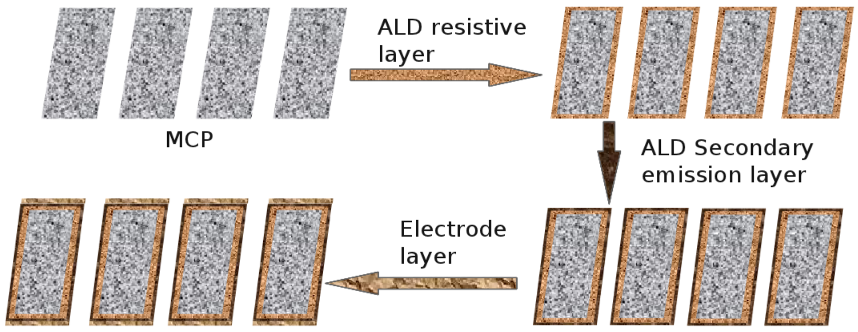
Status in 2011



Attempts to Reduce Aging

- Thin (5-10 nm) Al_2O_3 films at or between MCPs [NIM A629 (2011) 111]
- Improved vacuum quality
- Cleaning of MCP surfaces by electron scrubbing techniques
- Modified and more robust photo cathodes [JINST 6 C12026 (2011)]
- Deposition of ultra-thin atomic layer (MgO, Al_2O_3) on MCP substrate
  - MCP pores are coated in three steps
    - resistive layer
    - secondary electron emission (SEE) layer
    - electrode layer
  - Optimization of MCP resistance and SEE
    - for each film independently
    - higher gain at given HV
  - Arradiance Inc. → PHOTONIS, LAPPD, …

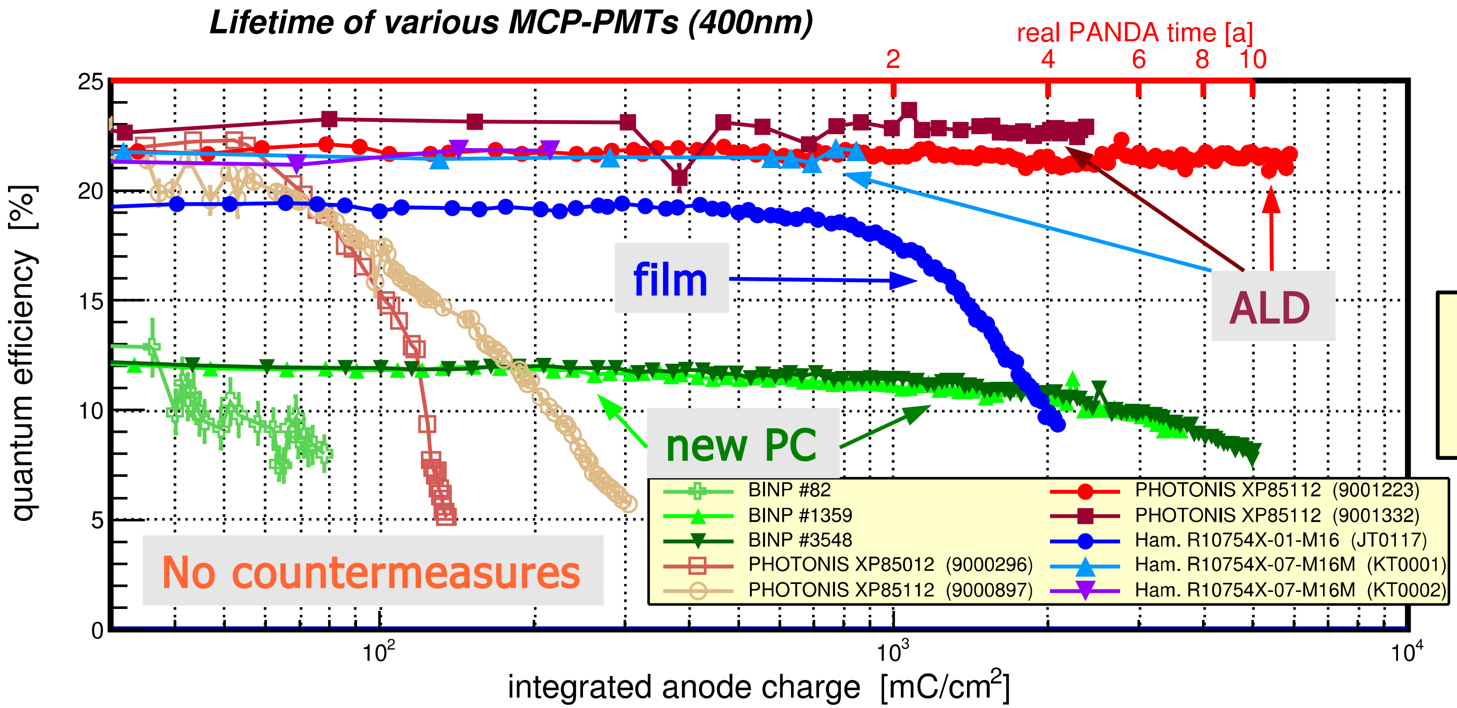
[NIM A639 (2011) 148]



!! most successful !!

Simultaneous Aging of MCP-PMTs

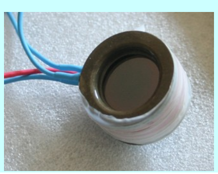
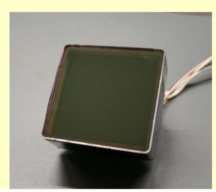
- **Problem in 2011:** The few aging tests existing were done in rather different environments → results are difficult to compare
- **Goal:** measure aging behavior for all available lifetime-enhanced MCP-PMTs in same environment
- **Simultaneous illumination** with common light source → same rate
- Aging results presented at RICH 2013:



ALD technique is superior

Lifetime-Investigated MCP-PMTs

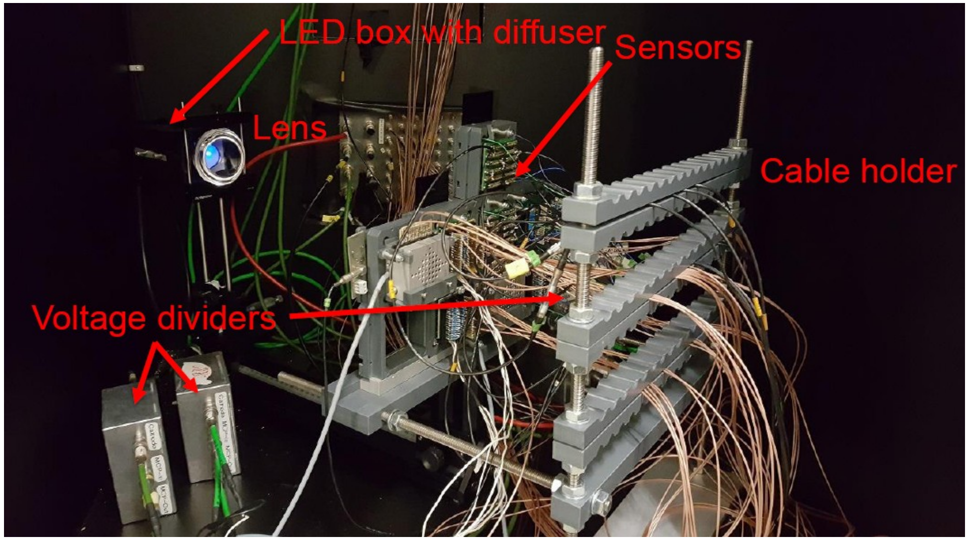
	BINP	PHOTONIS			Hamamatsu		
		XP85012	XP85112	XP85112	R10754X-01-M16	R10754X-07-M16M	R13266-07-M64
pore size (µm)	7	25	10	10	10	10	10
number of pixels	1	8x8	8x8	8x8	4x4	4x4	8x8
active area (mm²)	$9^2\ \pi$	53x53	53x53	53x53	22x22	22x22	51x51
total area (mm²)	$15.5^2\ \pi$	59x59	59x59	59x59	27.5x27.5	27.5x27.5	61x61
geom. efficiency (%)	36	81	81	81	61	61	70
photo cathode	Multi-alkali		bi-alkali			multi-alkali	
peak Q.E.	21% @ 495 nm	20% @ 380 nm	23% @ 380 nm	22% @ 380 nm	21% @ 375 nm	22% @ 415 nm	17% @ 415 nm
comments	**better vacuum, new cathode**	better vacuum, polished surfaces	better vacuum, polished surfaces	**better vacuum, ALD surfaces**	**film between MCPs**	**ALD + film**	**ALD + film**
# of tubes measured	**2**	**1**	**1**	**3**	**1 (+1 L4)**	**2**	**4**

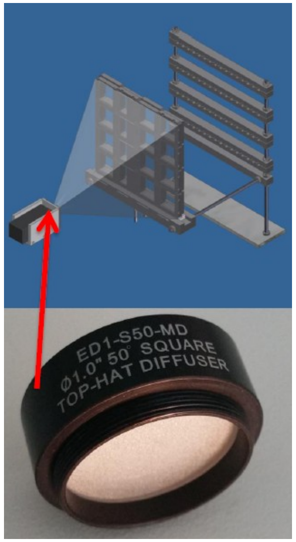

- Tubes first measured with no significant lifetime improvements
- Lifetime improved tubes measurement started ~6 years ago
- Hamamatsu 1 inch ALD tubes measurement started ~4 year ago
- Hamamatsu 2 inch ALD tubes started in Dec. 2015 and Aug. 2016

Measurement of MCP Lifetime

- Continuous illumination
  - 460 nm LED at 1 MHz rate attenuated to 1-photon level → ~10-20 mC/cm^2/day
  - All MCP-PMTs in same light spot
  - Permanent monitoring of MCP pulse heights and LED light intensity

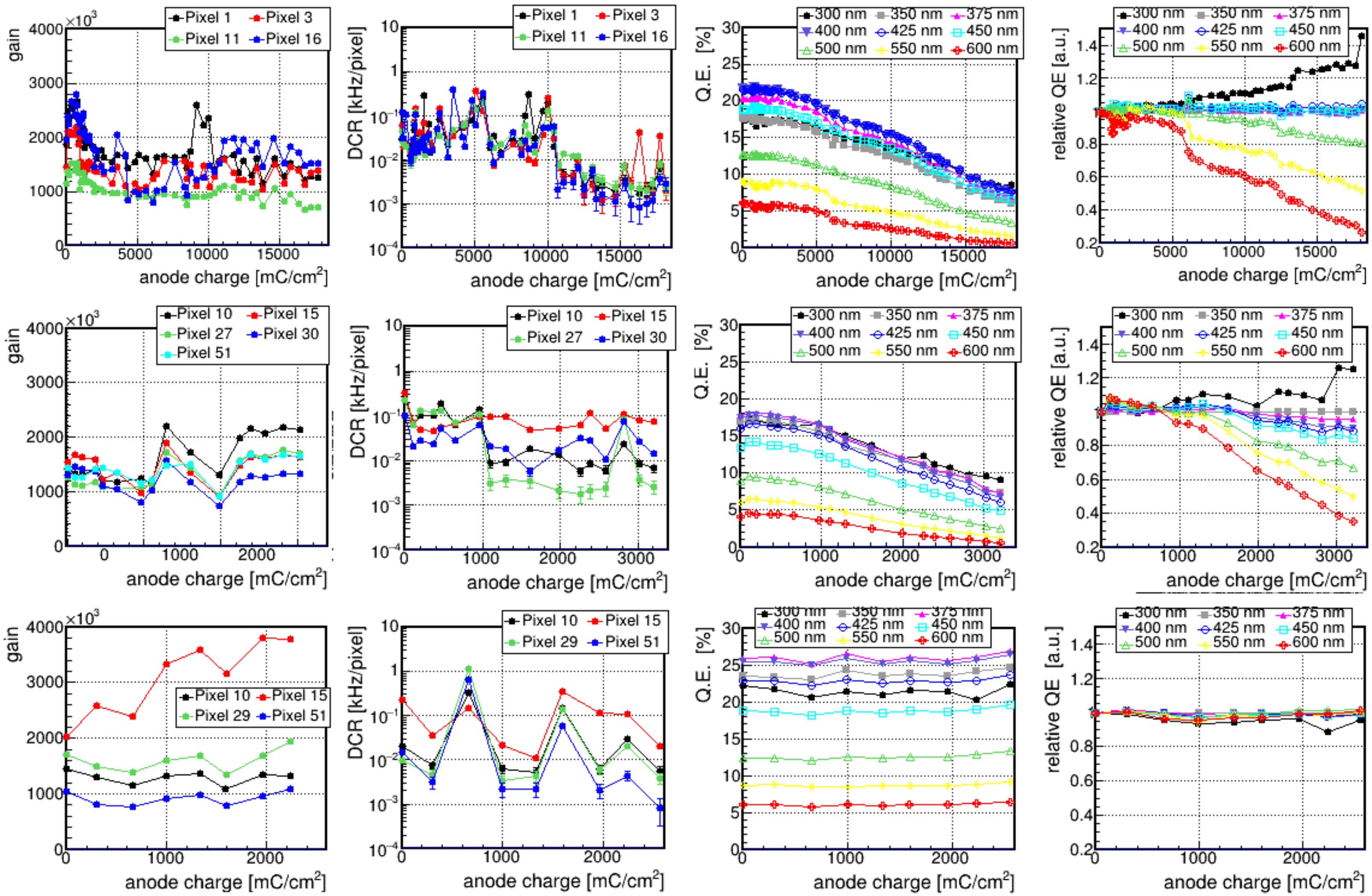


- Q.E. measurements
  - Light source: stable Xenon arc lamp
  - 250–700 nm wavelength band with in-house monochromator Δλ = 1 nm
  - Every ~4 weeks: wavelength scan
  - Every 3-4 months: complete surface scan at 372 nm
- Thorlabs square diffuser (ED1-S50-MD) in front of LED to get ~30x30 cm^2 homogeneously illuminated light spot at sensor plane
- Holding structure for up to 16 two-inch MCP-PMTs



Gain, DCR and QE (Hamamatsu ALD)

gain | dark count | Q.E. | relative Q.E.



R10754X-07-M16M (KT0001)

1-inch; 1 ALD layer + film between MCPs

R13266-07-M64 (JS0022)

2-inch; 1 ALD layer + film in front of 1st MCP

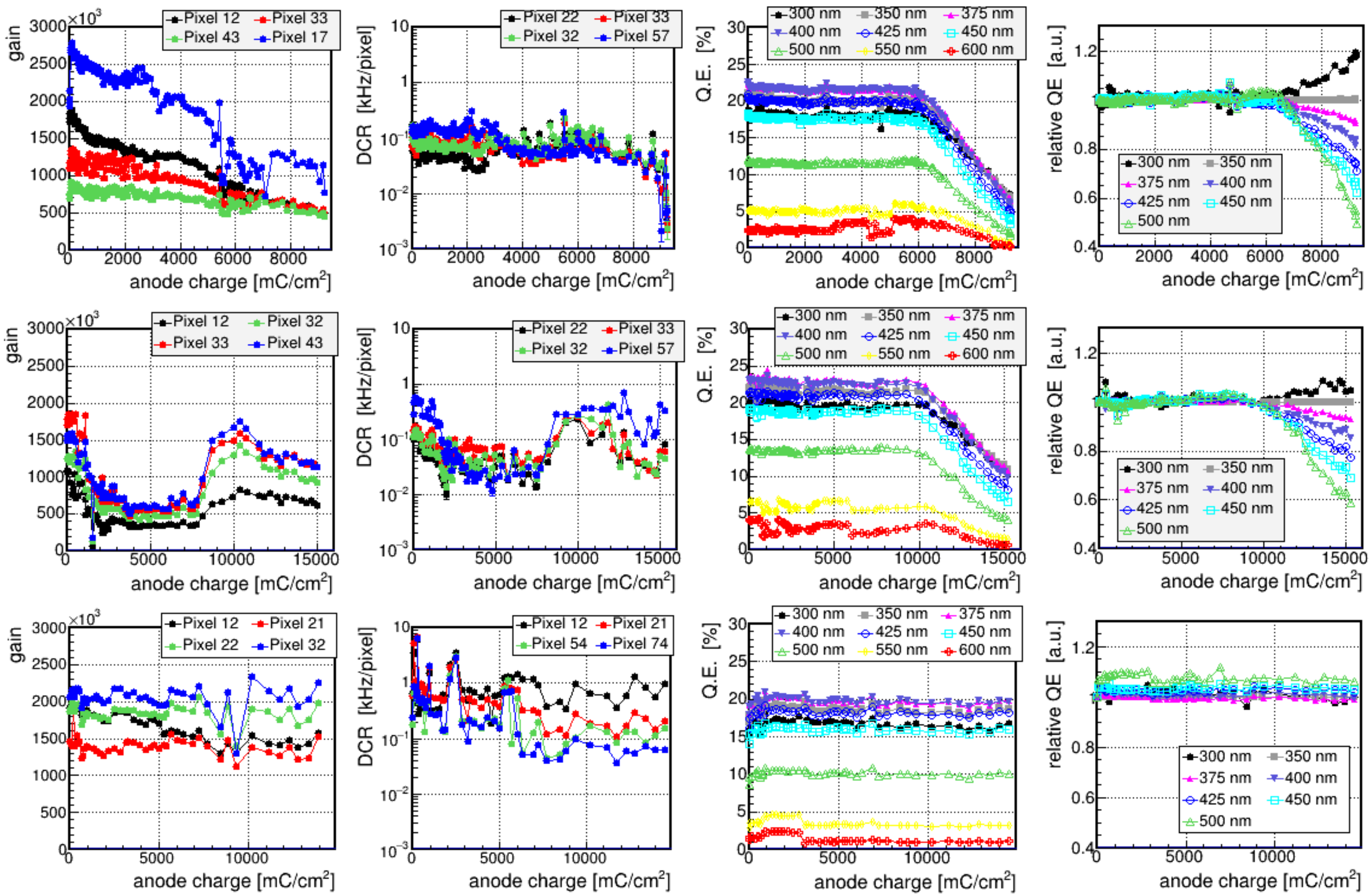
R13266-07-M64 (JS0035)

2-inch; 1 ALD layer + film in front of 1st MCP

- gain almost stable and DCR decreases only slightly
- when QE degrades clear wavelength dependence visible

Gain, DCR and QE (Photonis)

gain | **dark count** | **Q.E.** | **relative Q.E.**



XP85112 (9001223)

1 ALD layer

XP85112 (9001332)

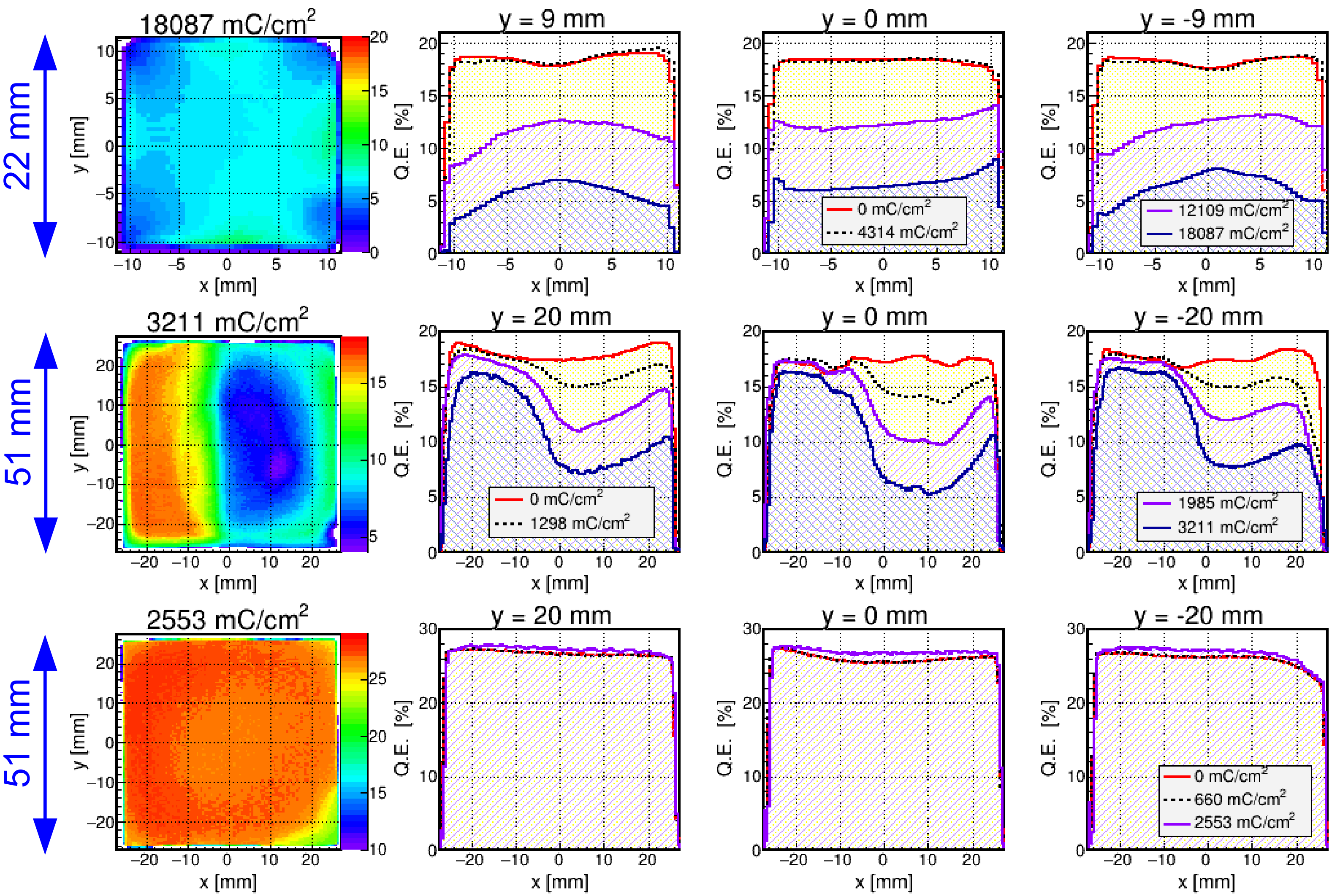
1 ALD layer

XP85112 (9001393)

2 ALD layers

- 1 layer ALD: gain/DCR variations; QE stable up to 6 and 10 C/cm^2, then declining
- 2 layer ALD: very stable behavior up to >14 C/cm^2

Q.E. Scans (Hamamatsu ALD)



Q.E. at 372 nm

R10754X-07-M16M (KT0001)

1 ALD layer
+ film between MCPs

R13266-07-M64 (JS0022)

1 ALD layer + film
In front of 1st MCP

R13266-07-M64 (JS0035)

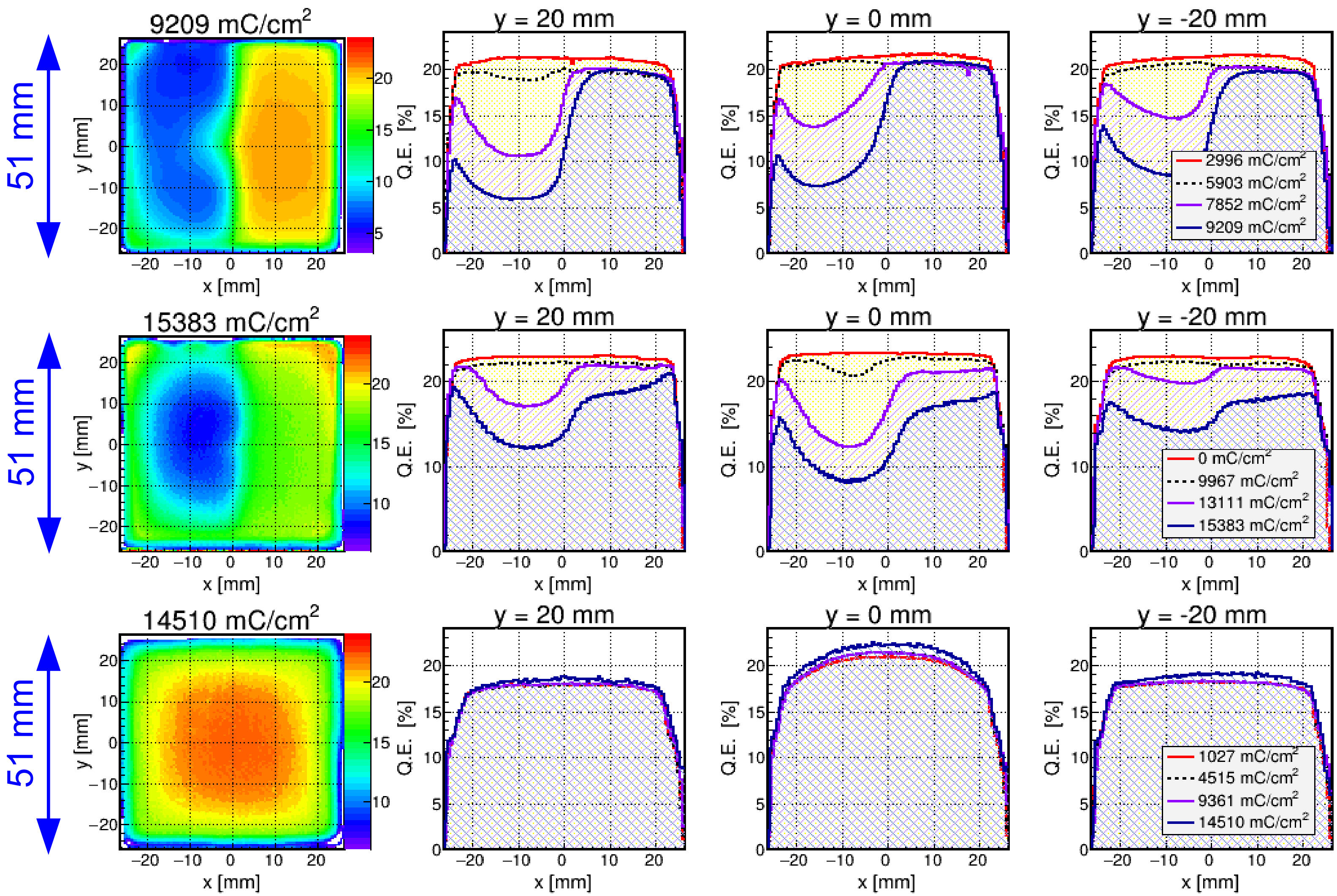
1 ALD layer + film
in front of 1st MCP

left half of tube not illuminated

1": stable to 4 C/cm^2, then moderate QE decline ; corners more serious
2": early QE degradation at JS0022; later prototypes (JS0035) stable

Q.E. Scans (Photonis ALD)

Q.E. at 372 nm



XP85112 (9001223)

1 ALD layer

XP85112 (9001332)

1 ALD layer

right half of tube not illuminated

XP85112 (9001393)

2 ALD layers

tube fully illuminated

1 ALD layer: QE degradation starts at 6 C/cm^2 and 10 C/cm^2

2 ALD layers: no sign of QE degradation up to >14.5 C/cm^2

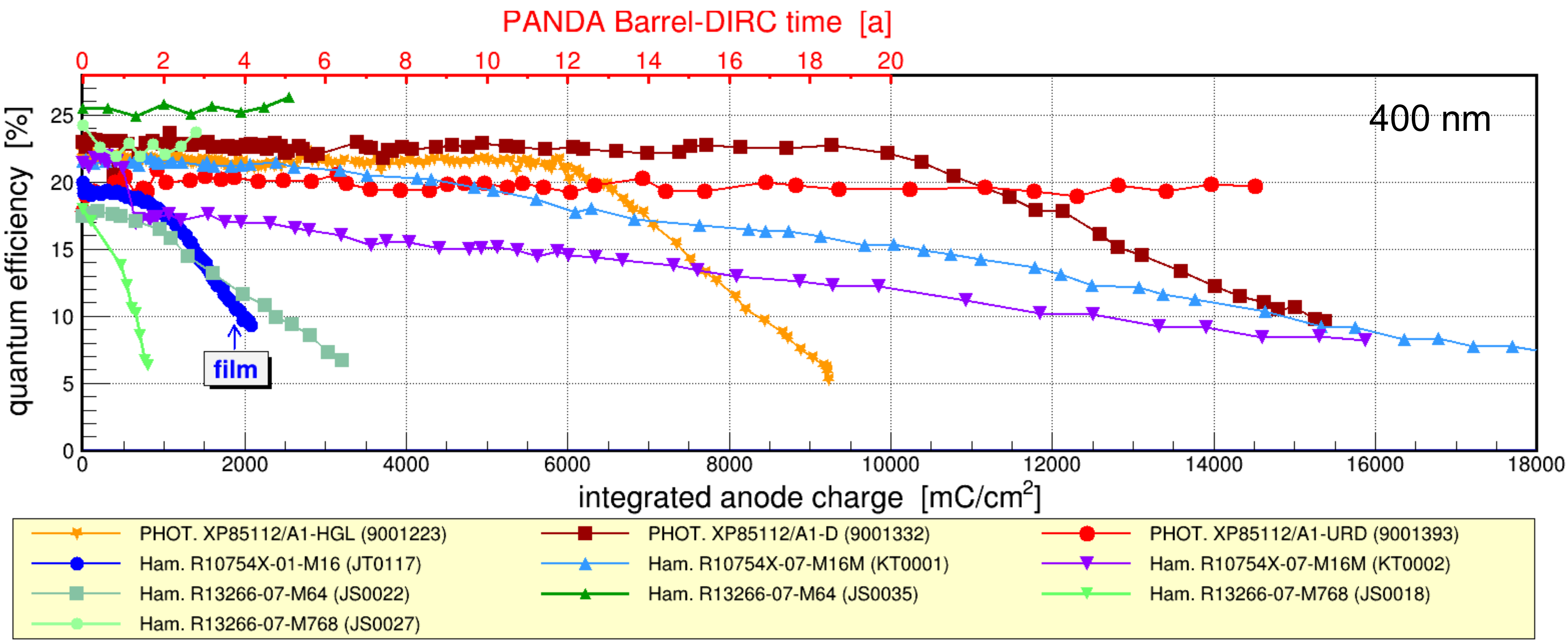
Illumination Overview

non – ALD

ALD

	Sensor ID	Integral charge (July 27, 2017) [mC/cm²]	QE start [%]	QE latest [%]	QE latest / QE start [%]	Comments
Photonis XP85112	9001223	**9234**	22.15	5.29	**24%**	Start: 23 Aug. 11 Stop: 22 Sep. 15
	9001332	**15383**	22.96	9.63	**42%**	Start: 12 Dec. 12 ongoing
	9001393	**14510**	19.05	19.68	**103%**	Start: 23 Jan. 14 ongoing
Hamamatsu R10754X/R13266	JT0117 (M16)	**2086**	19.97	9.32	**47%**	Start: 23 Aug. 11 Stop: 24 Jul. 12
	KT0001 (M16M)	**18097**	21.52	7.3	**34%**	Start: 20 Aug. 13 ongoing
	KT0002 (M16M)	**15872**	21.4	8.22	**38%**	Start: 21 Oct. 13 ongoing
	JS0022 (M64)	**3211**	17.43	6.73	**39%**	Start: 11 Dec. 15 ongoing
	JS0035 (M64)	**2553**	25.47	26.36	**103%**	Start: 31 Aug. 16 ongoing
BINP	3548	**6698**	11.93	4.58	**38%**	Start: 21 Oct. 11 Stop: 08 Jul. 15

Lifetime of ALD MCP-PMTs (07/2017)

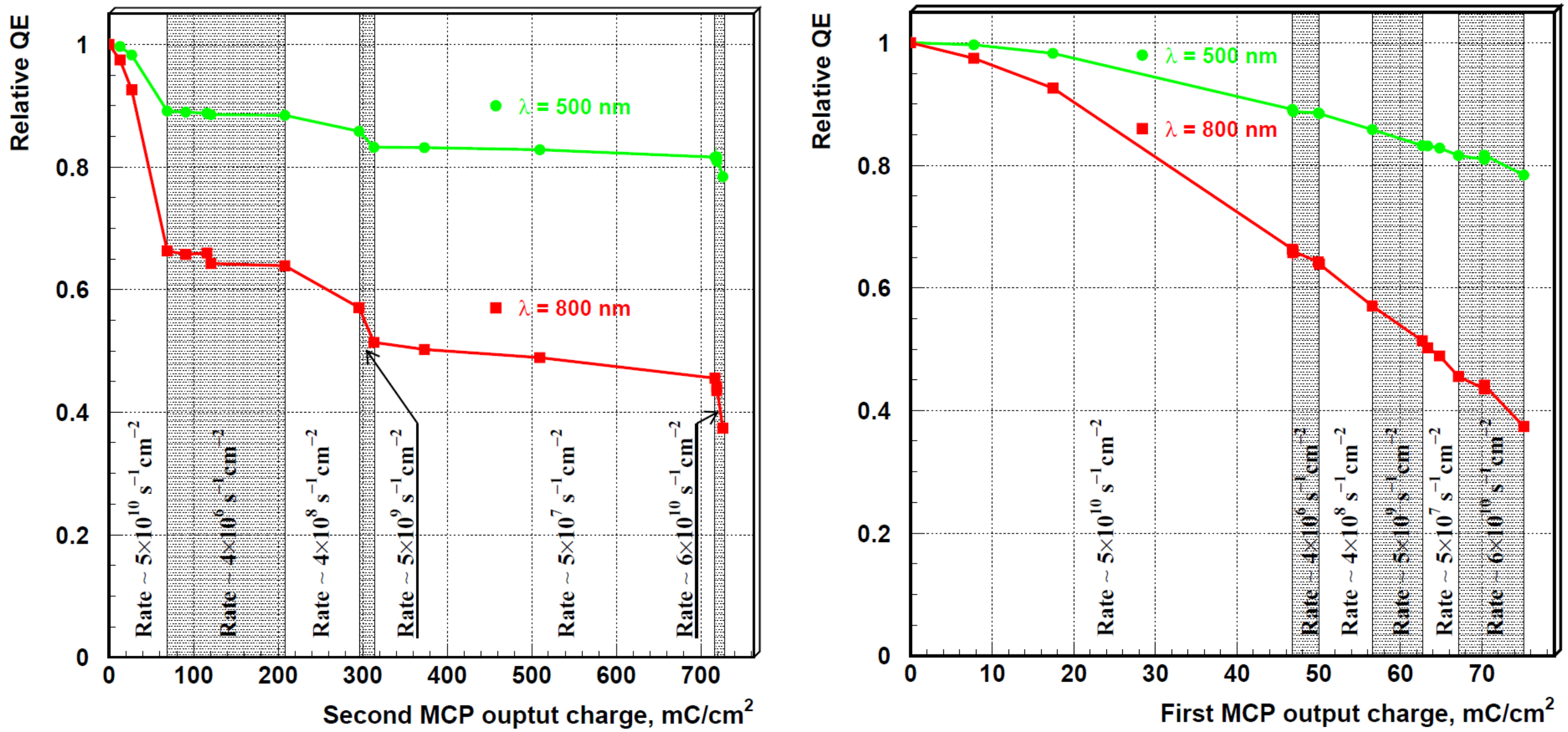


- 1-inch ALD Hamamatsu: 50% of original QE after ~14 C/cm^2
- 2-inch ALD Hamamatsu: later prototypes more stable
- 1-layer ALD PHOTONIS: aging starts at 6 and 10 C/cm^2
- 2-layer ALD PHOTONIS: **no sign of aging yet at 14.5 C/cm^2**

Accelerate Aging Measurements

M.Yu. Barnyakov and A.V. Mironov, 2011 JINST 6 C12026

2nd MCP

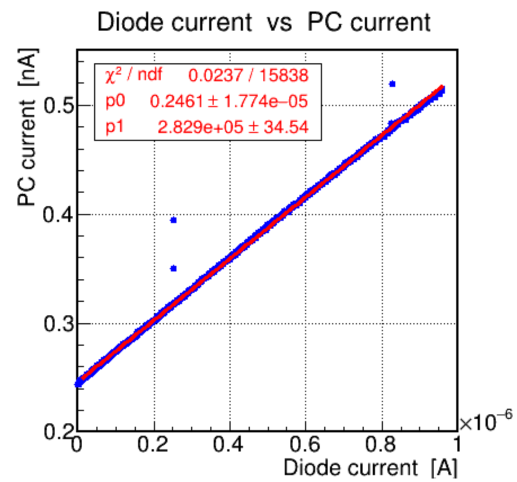


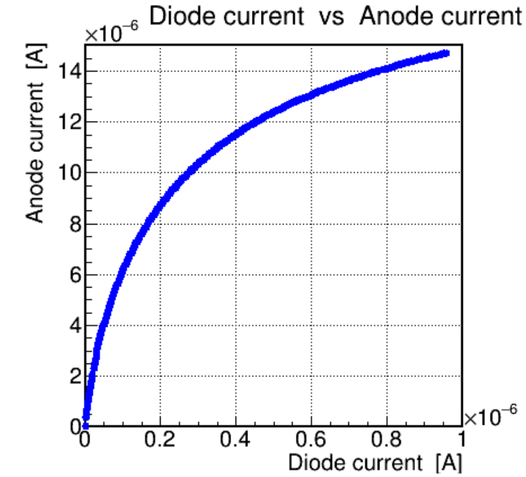
1st MCP or PC

- At 2nd MCP output the QE degradation rate depends on photon rate
- At 1st MCP (or PC) no correlation between QE degradation and rate
- Simultaneous current measurement at cathode and anode requires one **potentialfree picoammeter** (up to 3.5 kV)

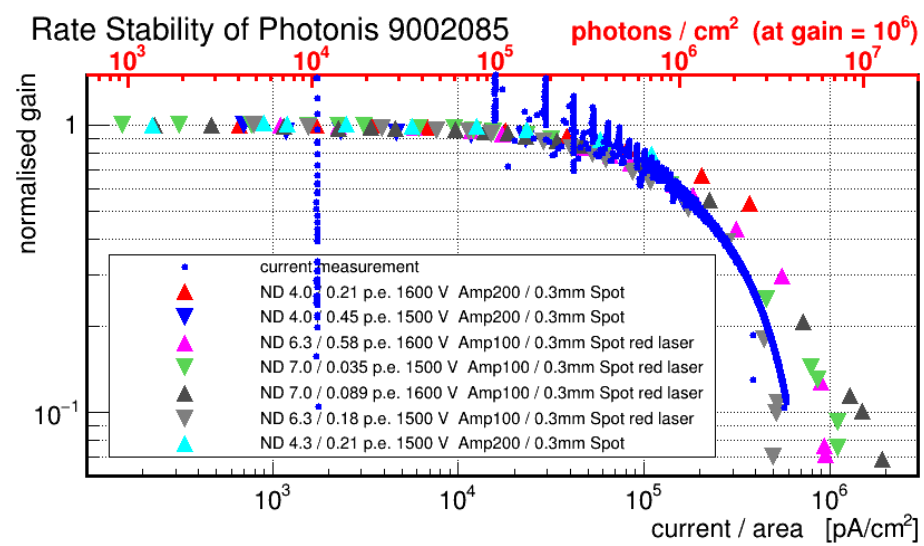
Tests with Floating Picoammeter

- Floating picoammeter (FPA)
  - Self-built, since commercially not available
  - Floating to 2 kV (new one to 4 kV)
  - Current to voltage conversion
  - Readout with standard multimeter
  - Very linear behavior down to ~1 pA





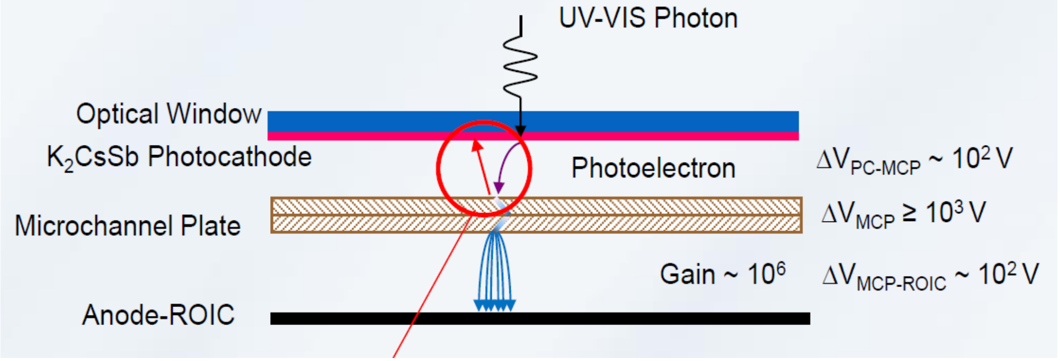
- Test measurements
  - Photonis 9002085 at 1600 V
  - Simultaneous illumination of MCP-PMT and photo diode with Pilas laser
  - 6 h dark, then increasing light intensity
  - PC current (FPA) proportional to light
  - Anode current (Keithley) saturates
  - Agreement with pulsed rate stability



Possible Causes of MCP Aging

- Neutral molecules from residual gas react with PC [NIM A629 (2011) 111]
- Ion feedback
  - Amplification process causes
    - Desorption of atoms from MCP material (especially H and Pb)
    - Damage to MCP surfaces gain may change
    - Ionization of residual gas atoms

[Jeff deFazio, PHOTONIS, 2016]



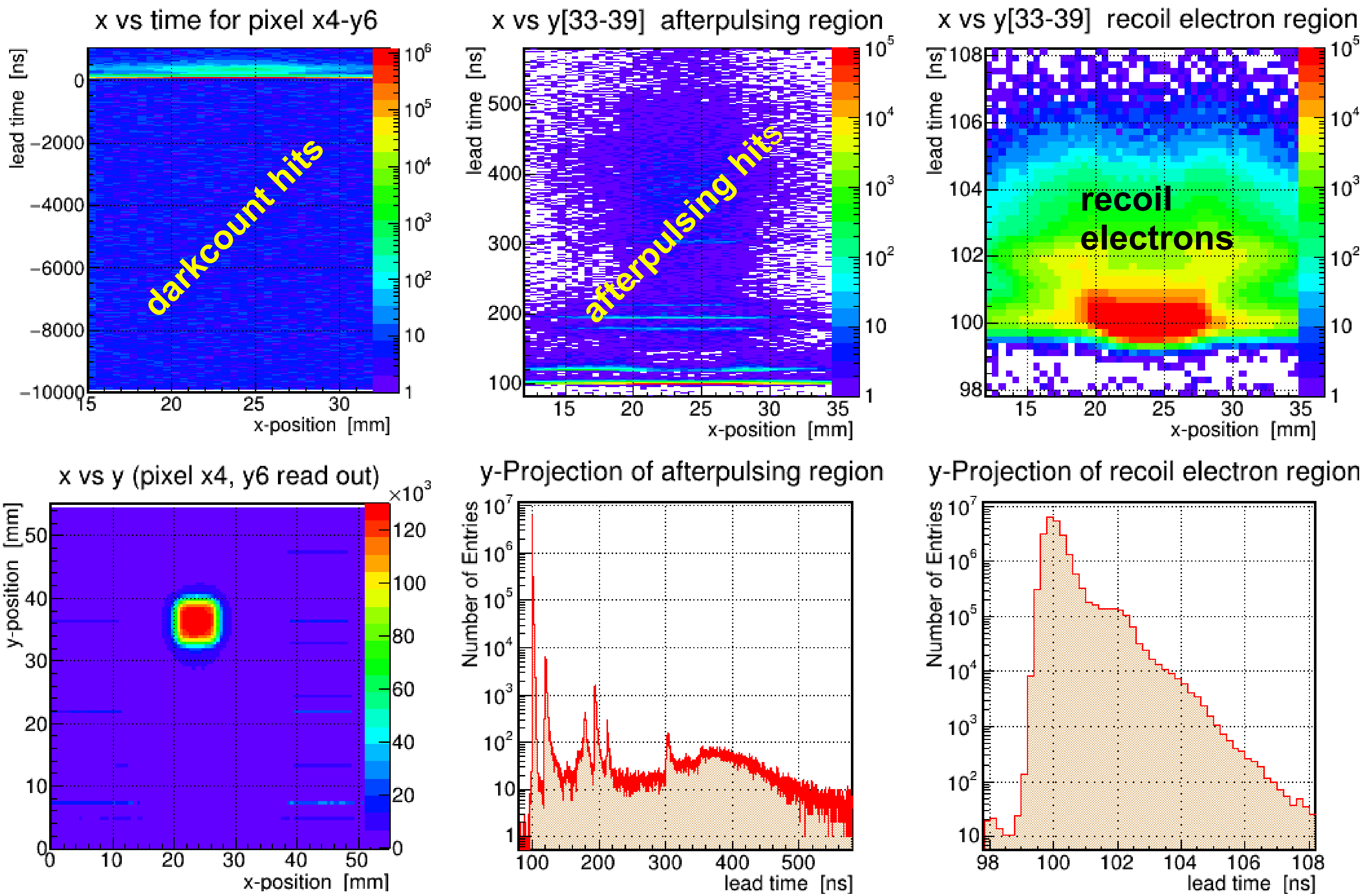
  - Ions accelerated towards photo cathode (**ion feedback**)
    - ~keV ions hit and may react with PC
    - Light (H^+, He^+, ...) and heavier ions (Si, K, Cs, Pb, ...) partly confirmed by TOF
  - PC gets damaged → QE loss → **Mechanism unknown !**
  - Findings from investigation of Photonis 9001223 (with aged/unaged PC halves)
    - Optical measurements → photon absorption unaffected → **no bulk damage**
    - Retarding potential analysis → shows only **minor effects on work function**
    - **Sputtering of Cs** from PC to MCP surface observed

Scans with TRB/PADIWA DAQ

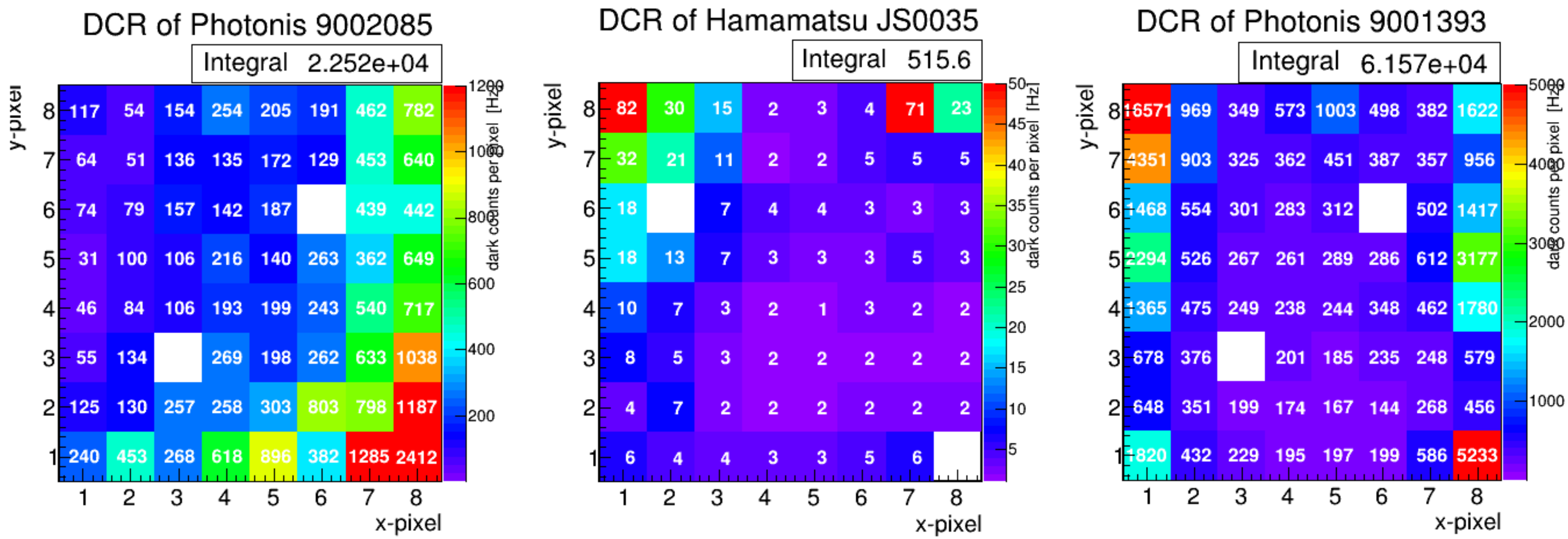
For details about TRB/PADIWA data acquisition see talk of M. Traxler

- Each channel: TRB system is permanently analyzing data stream and buffering PADIWA lead time and time-over-threshold (ToT) information of hits
- After a trigger (t = 0) all hits within a certain time interval (e.g. -10 to +10 μs) are read out and stored; in our case the trigger is usually given by the Pilas laser
- Main information per channel obtained with xy-scans
  - x-, y-position, lead time, ToT, number of hits
- Higher level information deduced (currently):
  - Afterpulse distributions → TOF of feedback ions
  - Dark count xy-distributions
  - Charge sharing (and electronic) crosstalk (>= 2 hits at same time)
  - Recoil electron distributions (spatial information and time delay)
- TRB scans allow the **separation of hits from recoil electrons and those of charge sharing events as well as identification of afterpulsing hits**

TRB-Scan of PHOTONIS Hi-QE

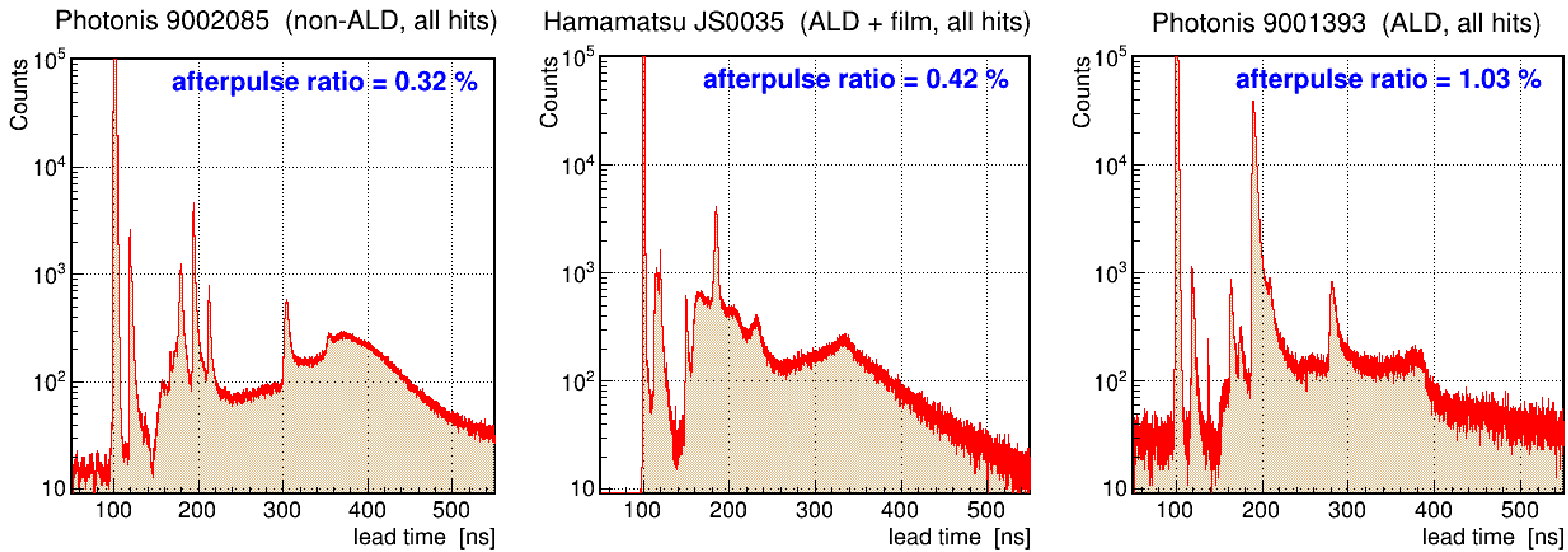


Comparison of Darkcount Rates



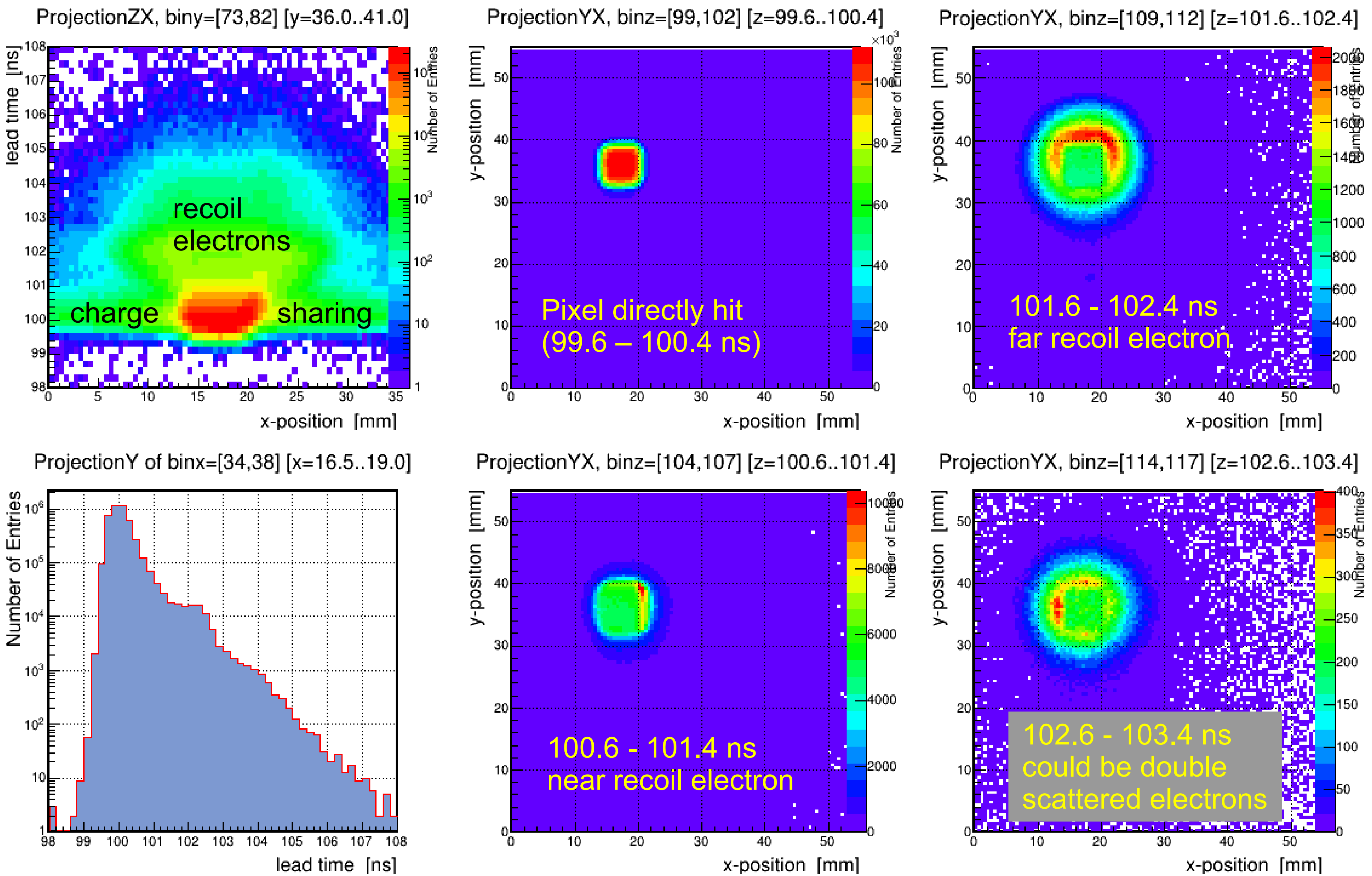
- Determine darkcount rate per pixel with integral of N(-10000 ns to 0 ns)
- Rate/pixel varies from <10 Hz to ~10 kHz
- By far lowest darkcount rate observed with Hamamatsu JS0035
- High darkcount rate in 2-layer ALD Photonis 9001393 (heavily aged!)
- Highest darkcount rates often seen in corner pixels

Afterpulse Distributions



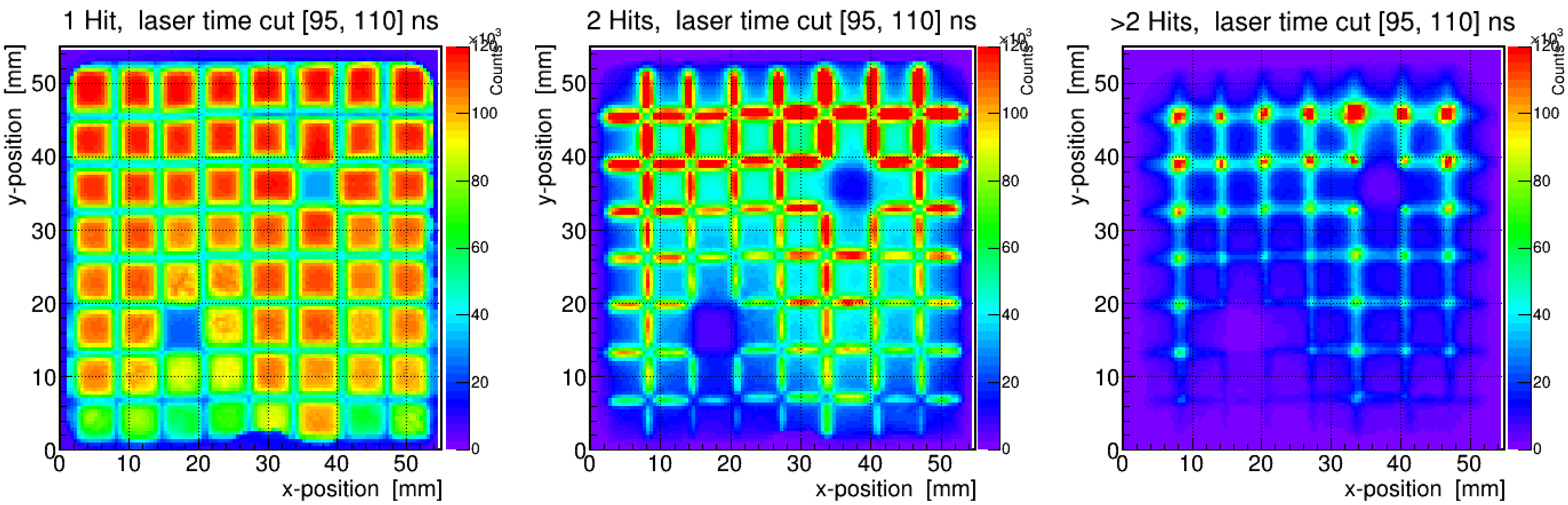
- Possibility to determine afterpulse rate (and distribution per pixel)
- % of afterpulses = N(115-550 ns) / N(98-115 ns)
- Several peaks in afterpulse distribution → possibility to identify ions
- Significant afterpulsing seen in Hamamatsu ALD tube with film (??)
- 9001393 with longest lifetime has also significant afterpulse fraction

Recoil e^- in PHOTONIS Hi-QE



Crosstalk in PHOTONIS 9002085

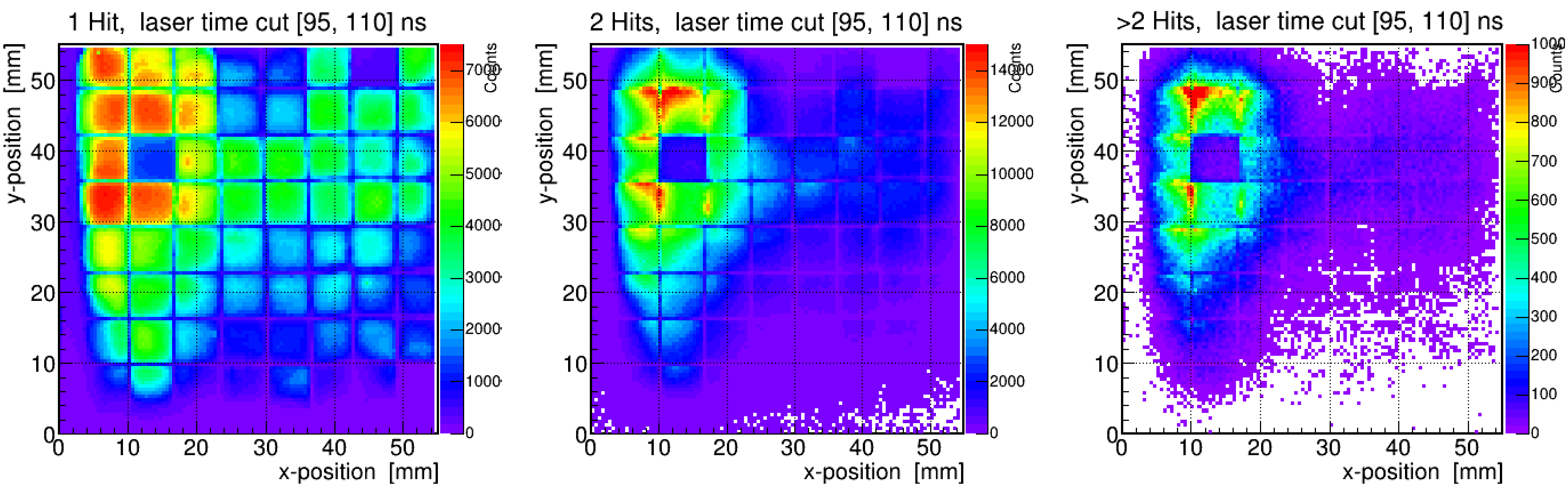
XP85012; 25 µm; non-ALD; high-QE; 1600 V



- Events with 1, 2, and >2 hits in time window between 95 and 110 ns
- 2 Hits (pixel borders) → charge sharing among 2 pixels (same time)
- >2 Hits (pixel corners) → charge sharing among 3 or 4 pixels
- Peak widths allow determination of charge cloud size → σ = 1.0 – 1.2 mm

Crosstalk in Hamamatsu JS0035

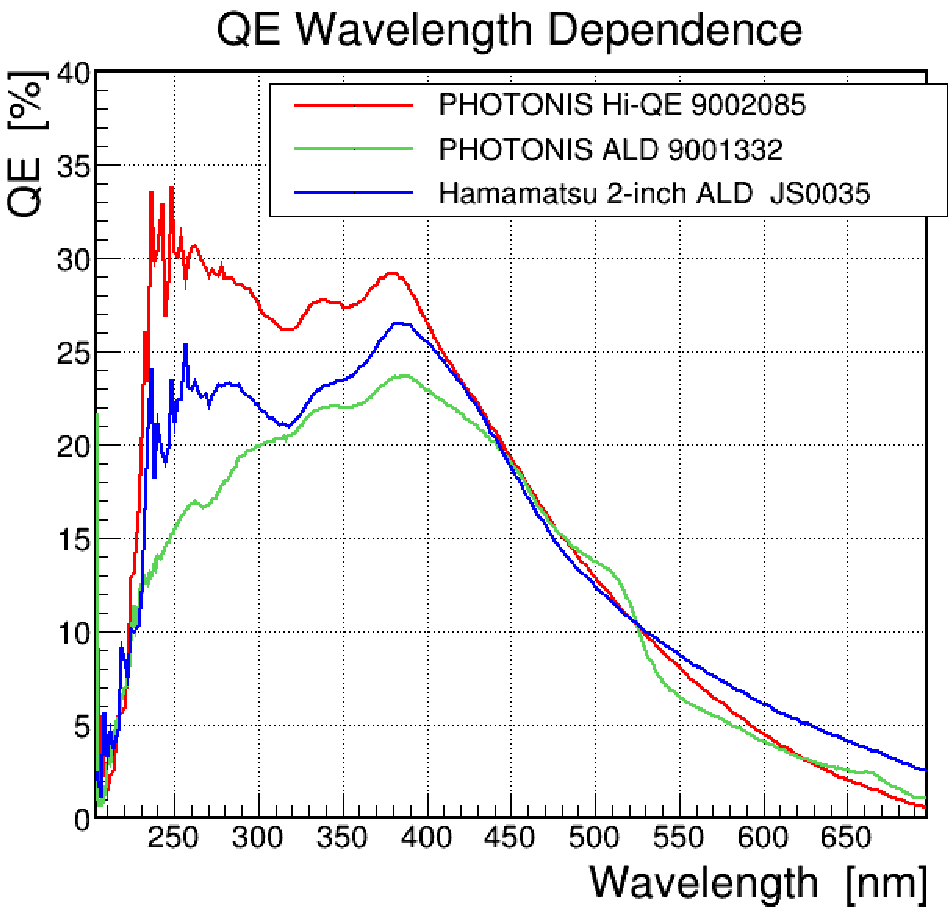
R13266; 2-inch; 10 µm; ALD + film in front of 1st MCP; 2800 V



- Events with 1, 2, and >2 hits in time window between 95 and 110 ns
- Pixel borders clearly seen in 1-hit distribution
- >=2 Hits (pixel borders) → no clear charge sharing seen !!
- Crosstalk behavior is very different to Photonis devices → **electronic crosstalk?**

QE Comparison of new MCP-PMTs

- PHOTONIS Hi-QE
  - 25 µm pores
  - No ALD coating
  - In HiQE tube the QE is significantly enhanced from 250 to 400 nm compared to older versions (e.g. 9001332)
  - Max. QE of 29% at 380 nm
- Hamamatsu 2-inch
  - 10 µm pores
  - ALD coating + film
  - Good QE of 27% at 385 nm

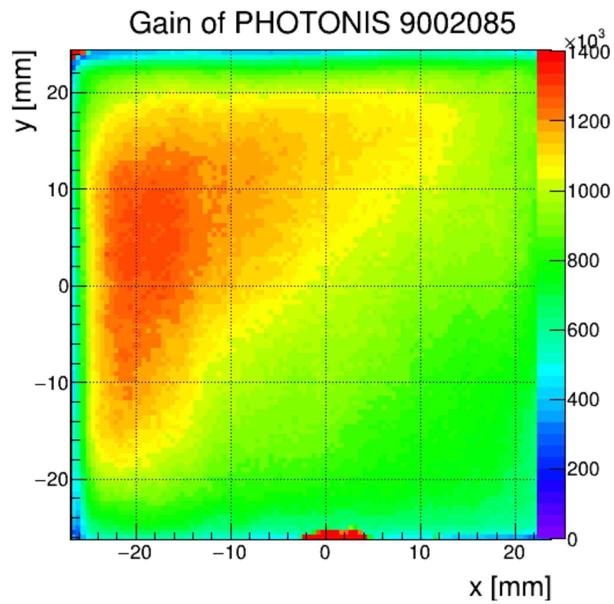


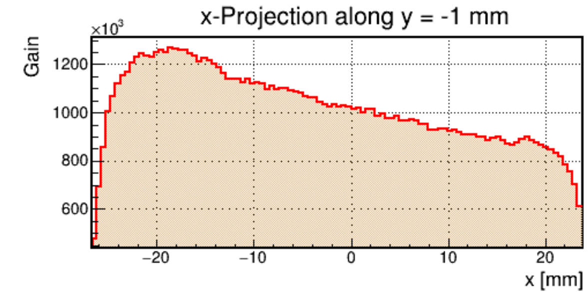
“Real” Gain of 2-inch MCP-PMTs

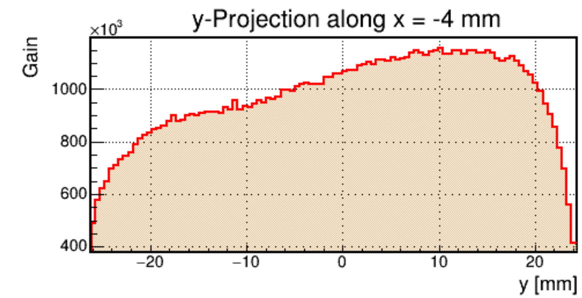
PHOTONIS Hi-QE 9002085
– U = 1600 V
– ~10^6 gain at center (pixel 44)
– **factor 2 gain variations**

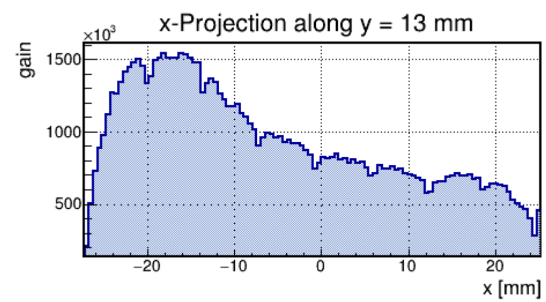
- Gain determined by ratio of current measurements at anode and PC (QE and CE cancel out)
- Measure direct PC current with unattenuated light
- Measure amplified current distribution obtained at shorted anodes with attenuated light

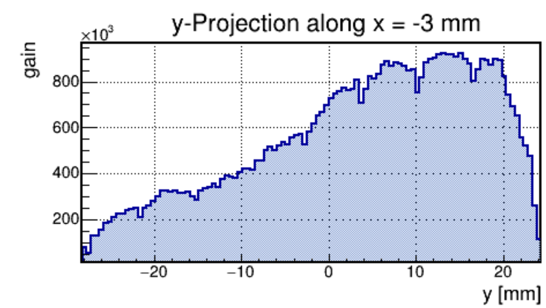
Hamamatsu 2-inch JS0035
– U = 2800 V
– ~$8 \cdot 10^5$ gain at center
– **factor 7 gain variation**

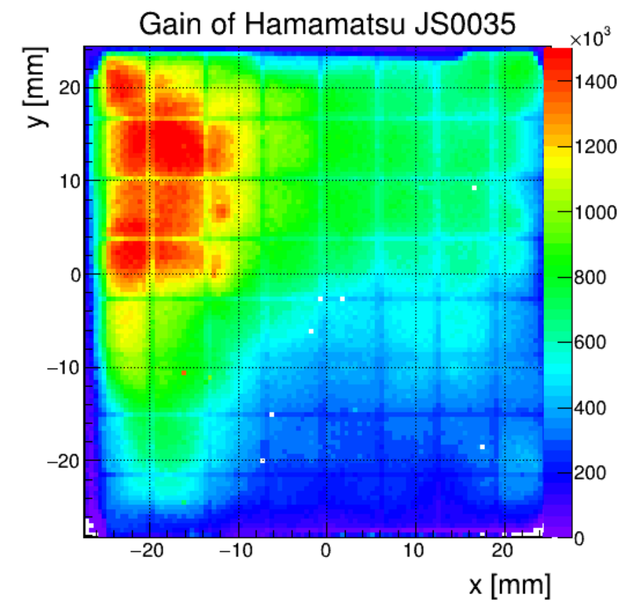




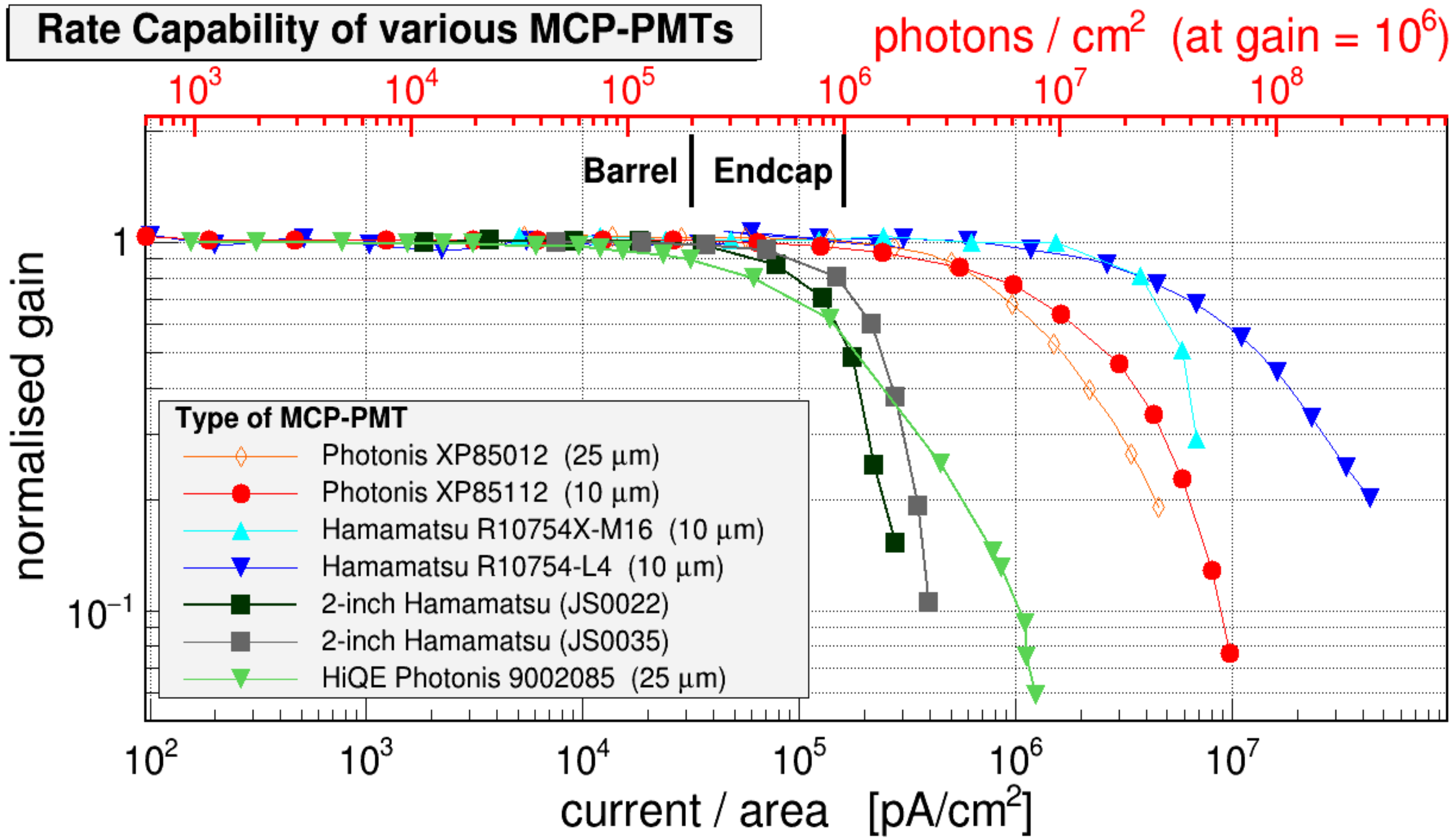








Rate Capability



- former MCP-PMTs showed stable operation to >1 MHz/cm² single photons
- Step from 1-inch to 2-inch MCP-PMTs (Hamamatsu) lowered rate capability by more than an order of magnitude (higher capacity?)
- Also new HiQE MCP-PMT from Photonis shows lower rate capability

Summary

- Last years have seen a **tremendous lifetime increase of latest MCP-PMT** models due to recent design improvements
  - **application of ALD technique (x50 lifetime improvement)**
  - **Huge step forward !**
  - **However: aging mechanism still not understood**
- Equipping the PANDA DIRCs and other high rate detectors with MCP-PMTs appears feasible
- Results of TRB scans look very promising and may provide a rich data set for many MCP-PMTs (especially when quality assurance tests are started)