Recent Progress with Microchannel-Plate PMTs

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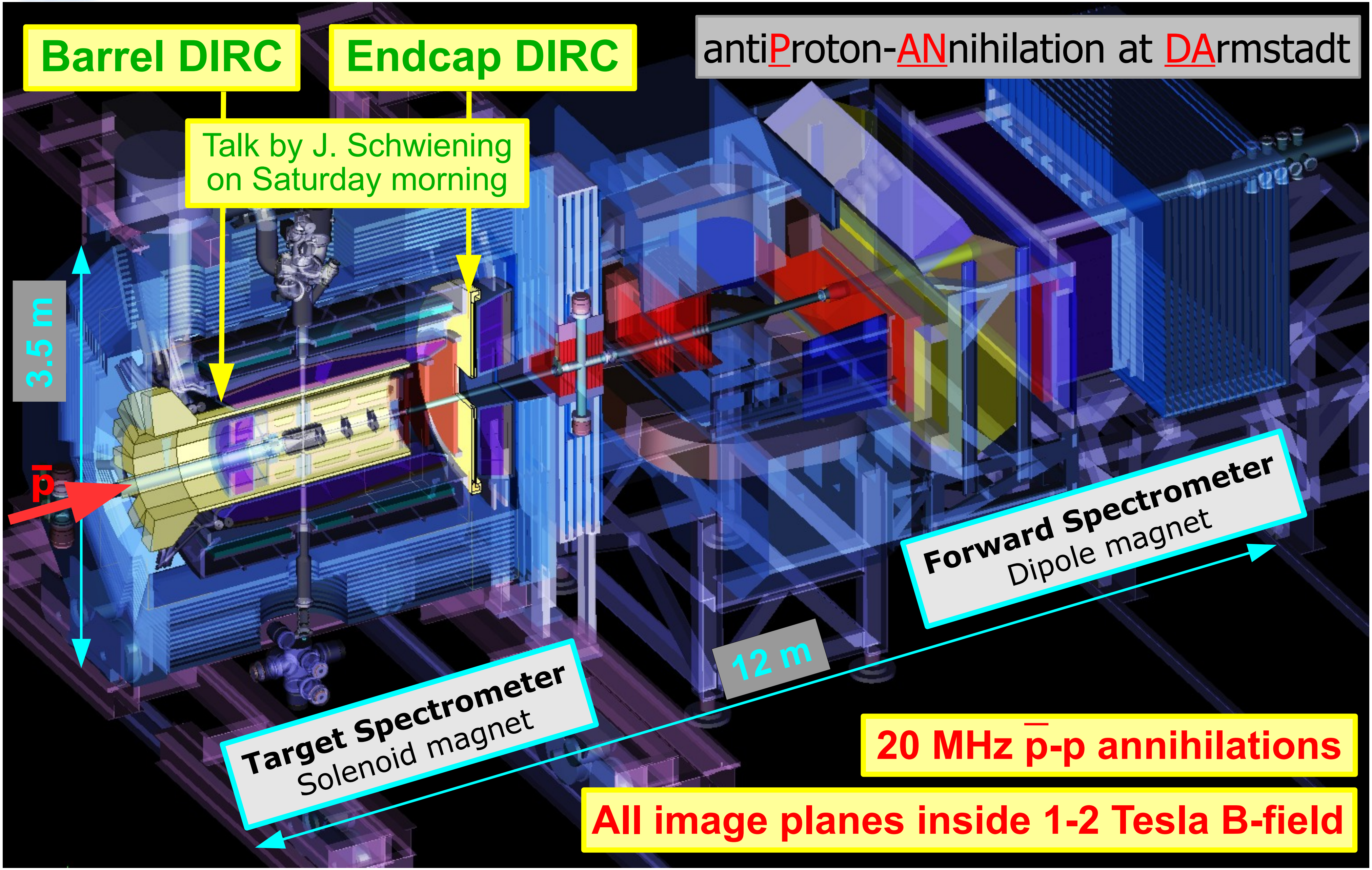
- Introduction and motivation
- Status of lifetime measurements
- Properties of the latest 2" MCP-PMTs
- New way to study darkcount, cross talk, recoil electron and afterpulsing events
- Summary and outlook

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

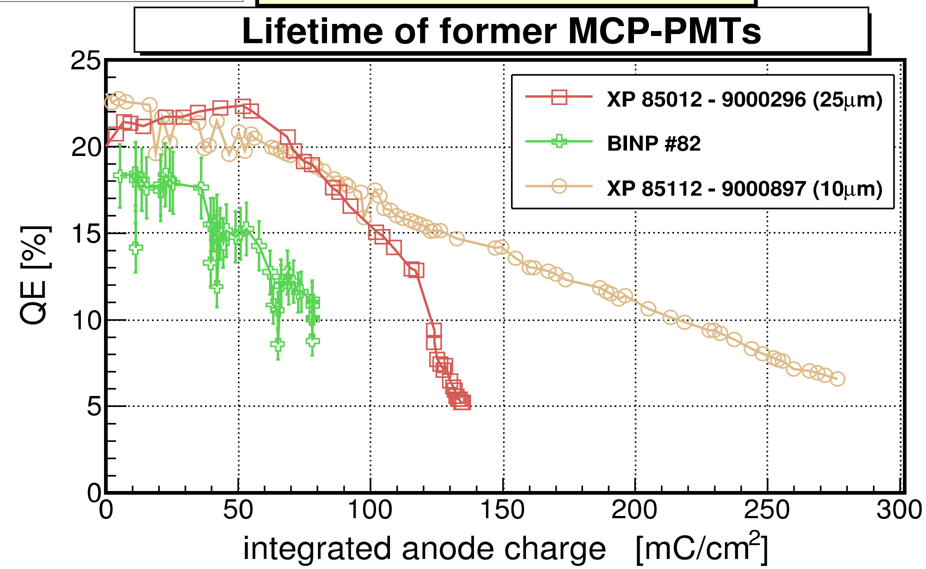


MCP-PMTs for PANDA DIRCs

- **MCP-PMTs are the only suitable sensors for PANDA**
- 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**

NIMA695 (2012) 68

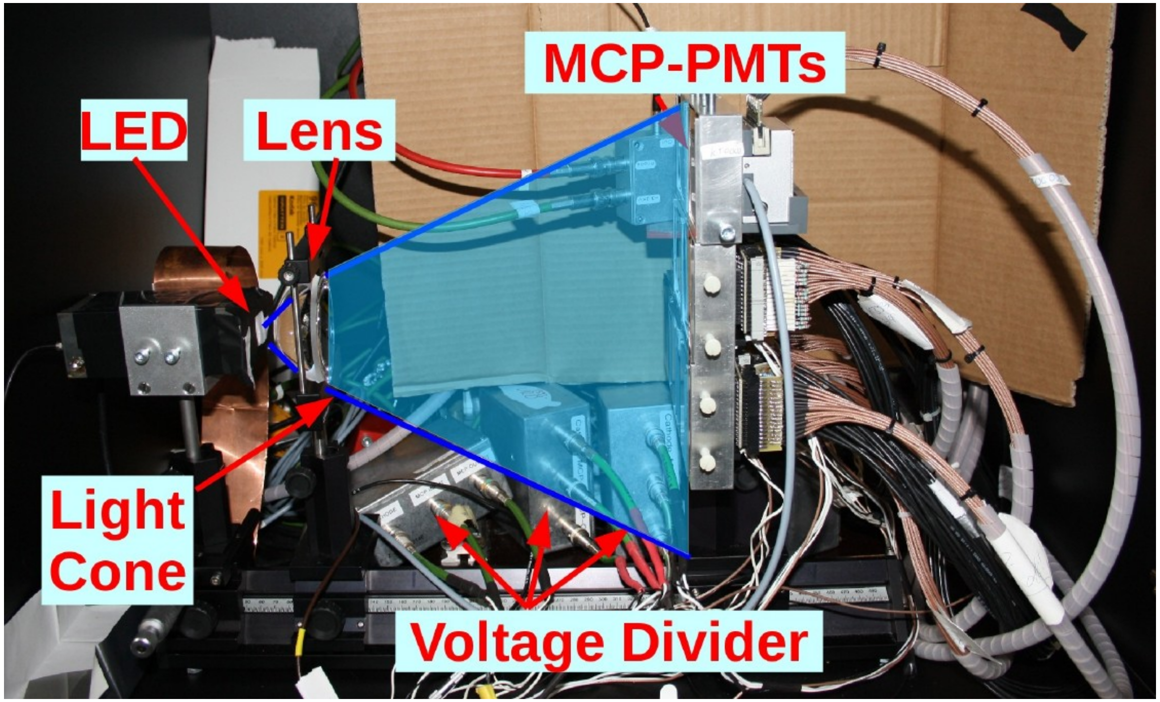
Status in 2011



- **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

Measurement of MCP Lifetime

- Continuous illumination
  - 460 nm LED at 0.25 to 1 MHz rate (comparable to PANDA DIRCs) attenuated to single photon level
  - All MCP-PMTs in same light spot (very homogeneous by using a thick lens and a Thorlabs diffuser)
  - Simultaneous illumination of up to sixteen 2-inch MCP-PMTs with current setup

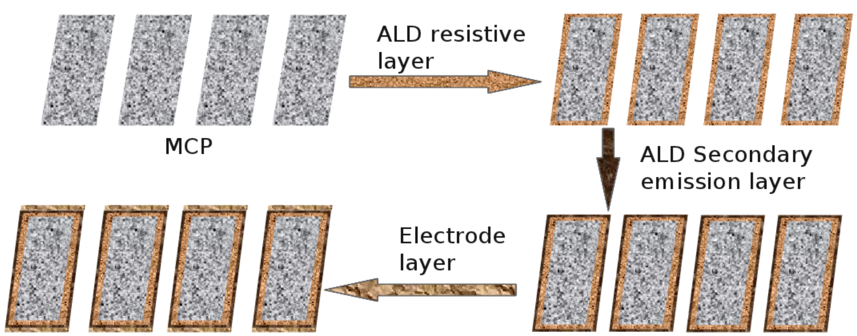


- Permanent monitoring
  - MCP pulse heights (rate highly prescaled) and LED light intensity
- Q.E. measurements
  - Light source: very stable Xenon arc lamp
  - 250–700 nm wavelength band with in-house monochromator Δλ = 1 nm
  - Every 3-4 weeks (at beginning days): wavelength scan
  - Every 3-4 months (at beginning weeks): complete surface scan at 372 nm

Attempts to Reduce Aging

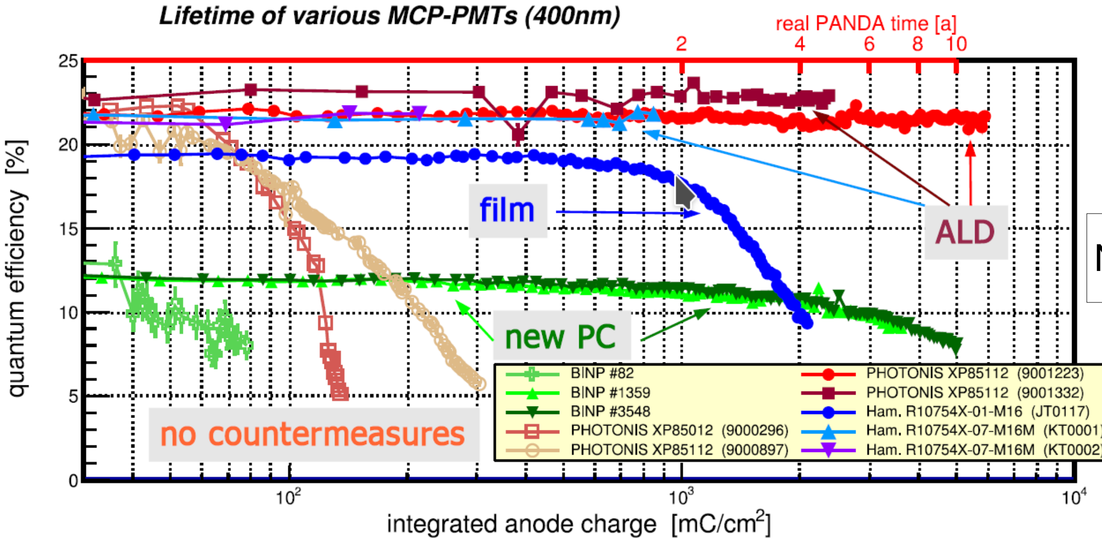
- First attempts (<2011): Improved vacuum quality and cleaning of MCP surfaces by electron scrubbing techniques
  - Only moderately successful (2 – 3x lifetime improvement)
- Thin (5-10 nm) Al_2O_3 films before or between MCPs [NIM A629 (2011) 111]
  - Lifetime improvement by factor ~10
- Modified and more robust photo cathodes [JINST 6 C12026 (2011)]
  - Moderate QE decline to >5 C/cm^2 but very high darkcount rates
- **Atomic Layer Deposition (ALD)**
  - MCP substrate coated by ultra-thin atomic layer (MgO, Al_2O_3) to reduce outgassing
  - Arradiance + ANL → LAPPD, PHOTONIS, ..
  - MCP pores are coated in three steps
    - resistive layer
    - secondary electron emission (SEE) layer
    - electrode layer

[NIM A639 (2011) 148]



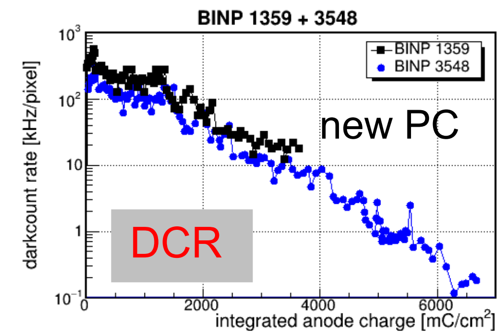
!! most successful !!

Results with non-ALD MCP-PMTs



NIMA766 (2014) 138

NIMA766 (2014) 138
JINST 11 (2016) C05009



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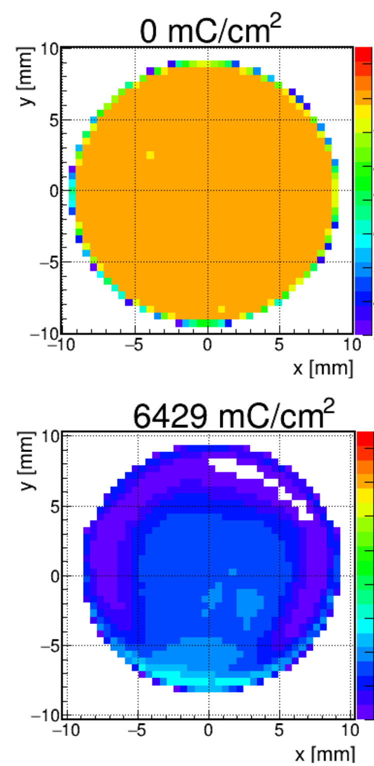
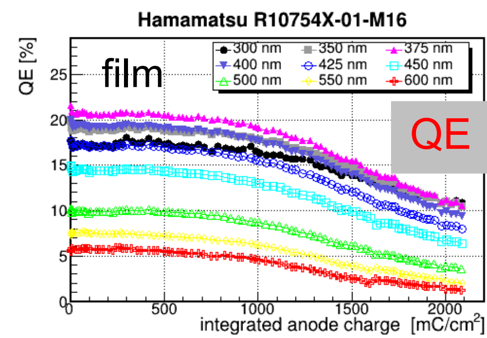
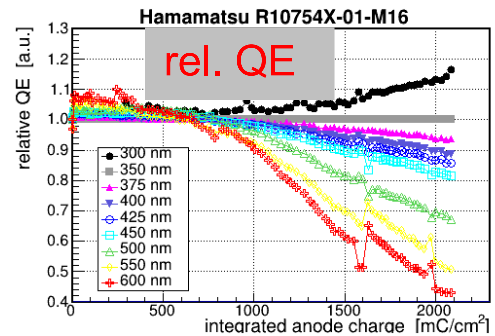






- PC ages with integrated anode charge (IAC)
  - film: QE good up to ~1 C/cm², then dropping
  - new PC: slow, but steady QE drop (>5 C/cm²)
  - factor ~10 improvement in lifetime
- Increasing IAC causes also
  - Moderate gain drop (factor 1-2)
  - Strong decline of DCR (factor 100 – 1000)
- When QE starts decreasing
  - **Faster aging for red light than for blue**
  - 2d-scans: usually PC aging starts and is more pronounced at rims and corners

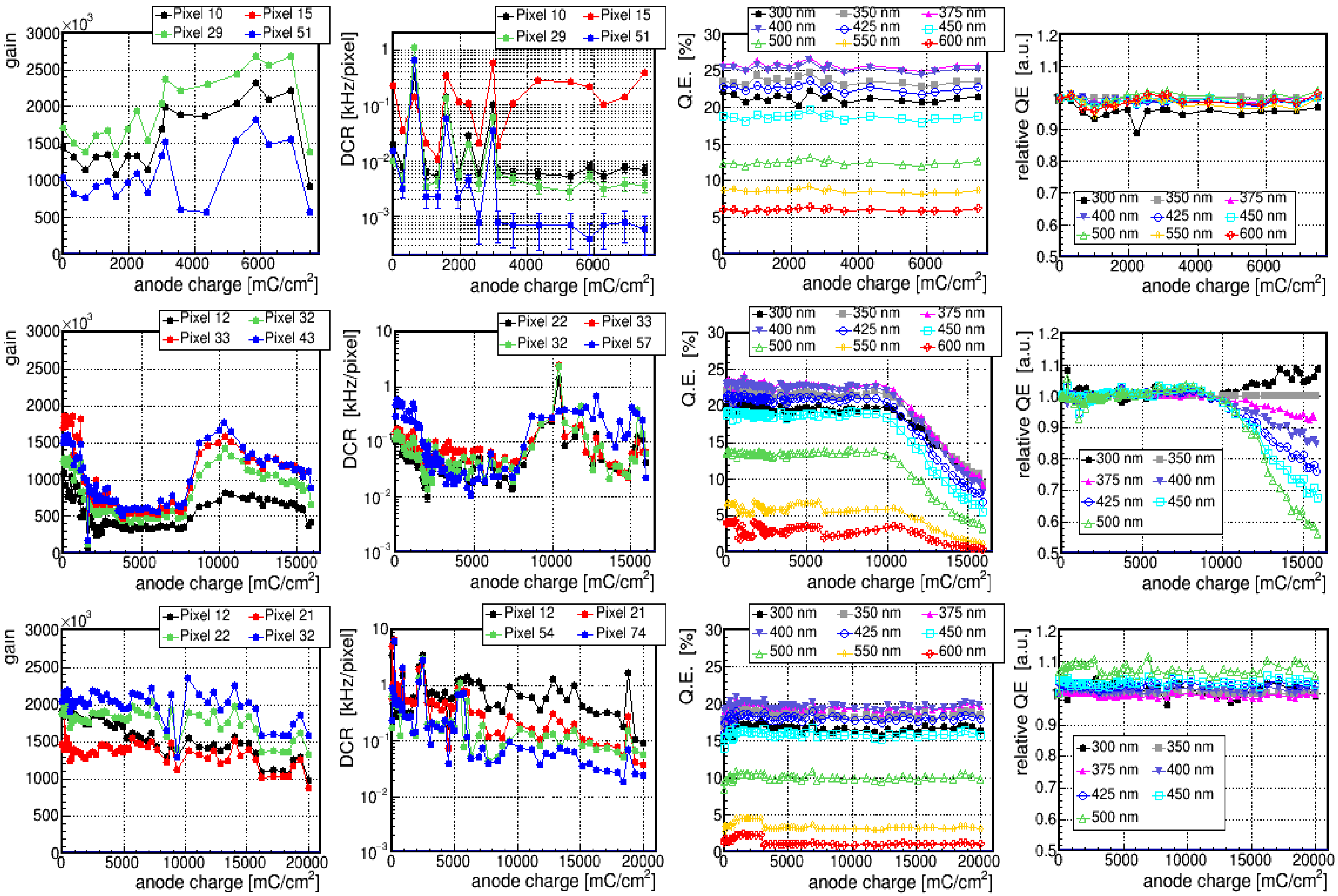
Investigated ALD-coated MCP-PMTs

	PHOTONIS			Hamamatsu			
	XP85112			R10754X-07-M16M	R13266-07-M64	R13266-07-M768	R13266-07-M64M
model	**9001223/1332**	**9001393**	**9002108**	**KT0001/0002**	**JS0022/0035**	**JS0018/0027**	**YH0250**
pore size (μm)	10			10	10		
number of pixels	8x8			4x4	8x8		
active area (mm²)	53x53			22x22	51x51		
total area (mm²)	59x59			27.5x27.5	61x61		
geom. efficiency (%)	81			61	70		
peak Q.E.	22% @ 380 nm	19% @ 380 nm	22% @ 380 nm	22/21% @ 415 nm	17/25% @ 415 nm	18/24% @ 415 nm	28% @ 380 nm
comments	**1 ALD layer**	**2 ALD layers**	**1 ALD layer**	**1 ALD layer**			
	normal CE (~65%)		**high CE (>90%)**	**film betw. MCPs**	**film in front of MCP-in**		**no film**
			UV-enhanced PC	**normal CE (~60%)**			

- First ALD-coated MCP-PMT from PHOTONIS received in mid 2011
- ALD-coated (with film) 1-inch Hamamatsu available from mid 2013
- ALD-coated 2-inch Hamamatsu shipped in mid 2015
- Recent 2-inch tubes from Photonis and Hamamatsu optimized for PANDA needs
  - high and uniform QE (and CE), gain and rate stability
  - low darkcount and afterpulse rates

Gain, DCR and QE (ALD MCP-PMTs)

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



R13266-07-M64 (JS0035)

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

XP85112 (9001332)

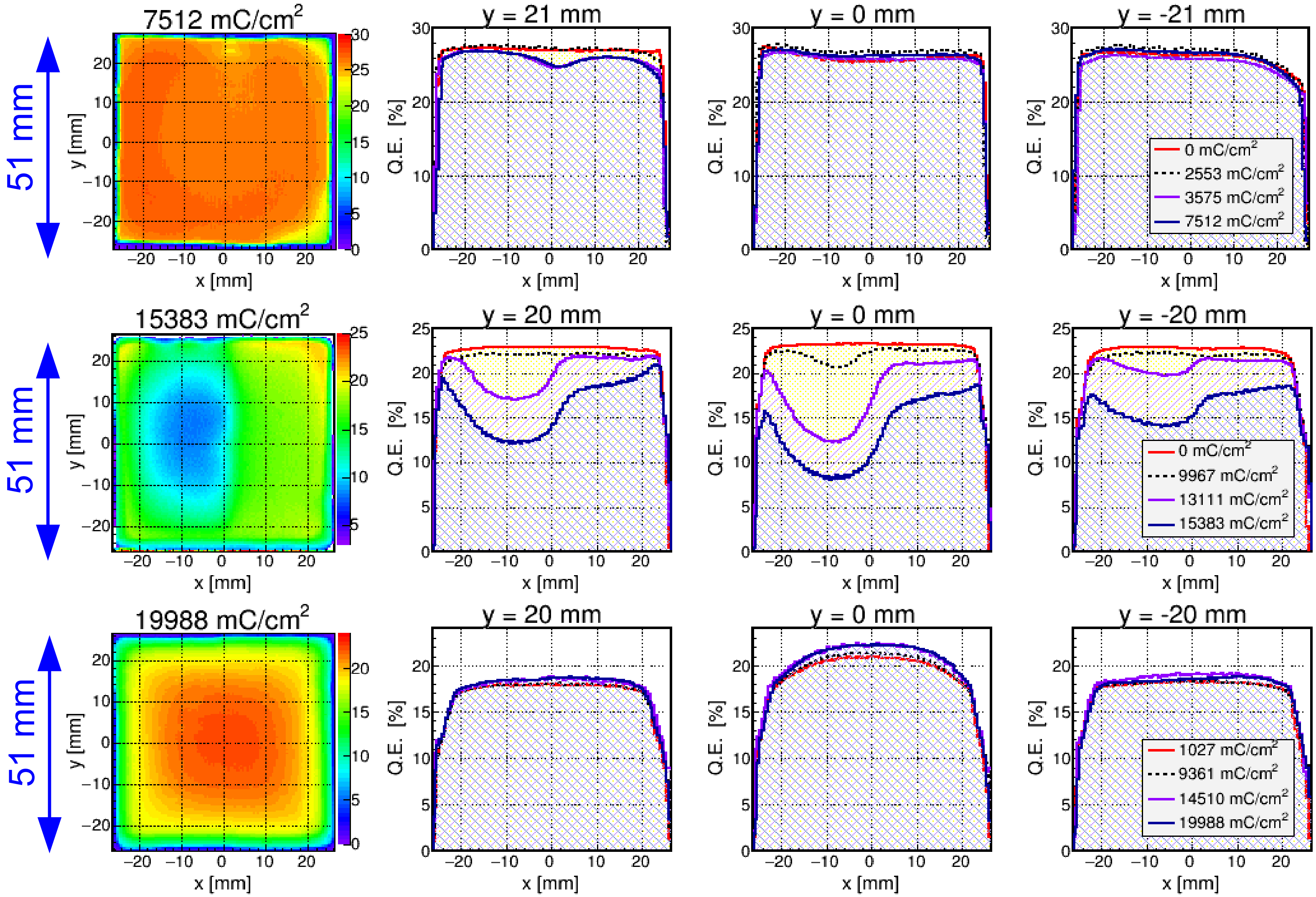
PHOTONIS; 2-inch; 1 ALD layer

XP85112 (9001393)

PHOTONIS; 2-inch; 2 ALD layers (R2D2)

- Phot. 9001332: gain/DCR variations; QE stable up to 10 C/cm², then declining
- **Ham. JS0035 and Phot. 9001393: stable up to 7.5 and 20 C/cm², respectively**

QE xy-Scans (ALD MCP-PMTs)



Q.E. at 372 nm

R13266-07-M64 (JS0035)

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

tube fully illuminated

XP85112 (9001332)

PHOTONIS; 2-inch; 1 ALD layer

right half of tube not illuminated

XP85112 (9001393)

PHOTONIS; 2-inch; 2 ALD layers (R2D2)

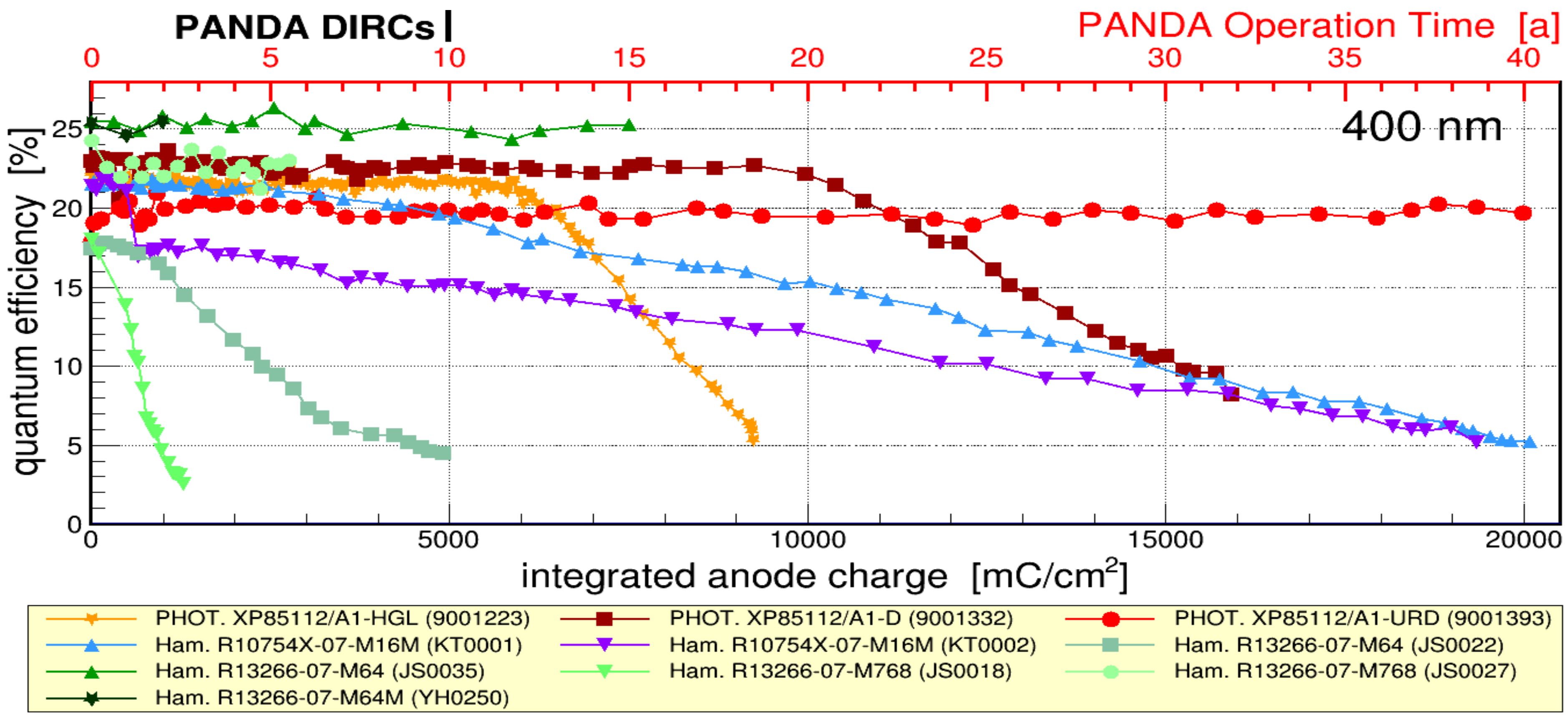
tube fully illuminated

Hamamatsu JS0035: except a tiny spot at upper rim no aging up to 7.5 C/cm^2

Phot. 1 ALD layer 9001332: aging after 10 C/cm^2 at left half → **ion feedback**

Phot. 2 ALD layers 9001393: **no sign of QE degradation up to 20 C/cm^2**

Lifetime of ALD MCP-PMTs (07/2018)

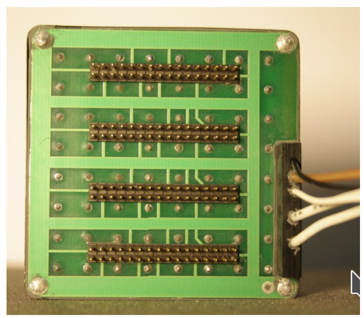


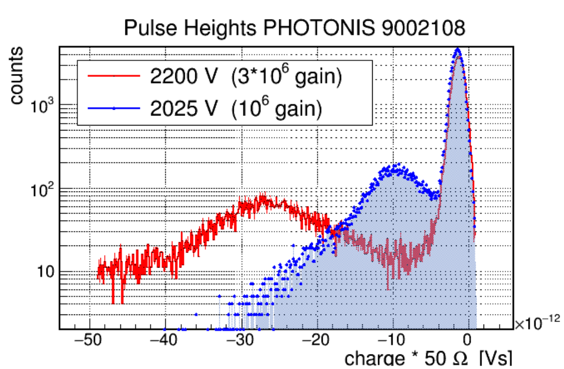
- 1-inch ALD Hamamatsu: 50% of original QE after 13 – 14 C/cm^2
- 2-inch ALD Hamamatsu: best tube at 7.5 C/cm^2 , wo film just started
- 1-layer ALD PHOTONIS: aging starts at 6 and 10 C/cm^2
- 2-layer ALD PHOTONIS: **no sign of aging up to 20 C/cm^2**

Latest 2” Multi-Anode MCP-PMTs

Photonis [JINST 13 C01047 (2018)]

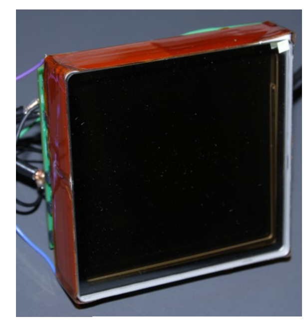
- layout existent since Burle Planacons
- improvements to catch most electrons bouncing at the MCP-in → **CE > 90%**
- 1-layer ALD surfaces; no film
- active area ratio: 81%
- available in 8x8 and 3x100 pixel layout

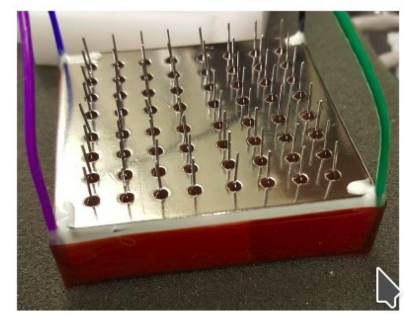


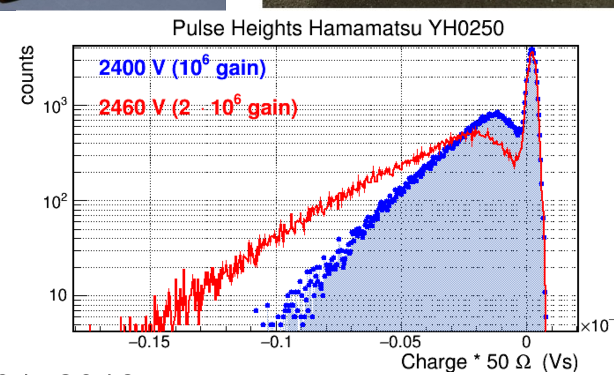


Hamamatsu

- first prototypes (2014) were with ALD surfaces + film in front of 1st MCP
- latest version is without a film to improve P/V ratio of pulse heights
- active area ratio: 70%
- available in 8x8 and 6x128 pixel layout





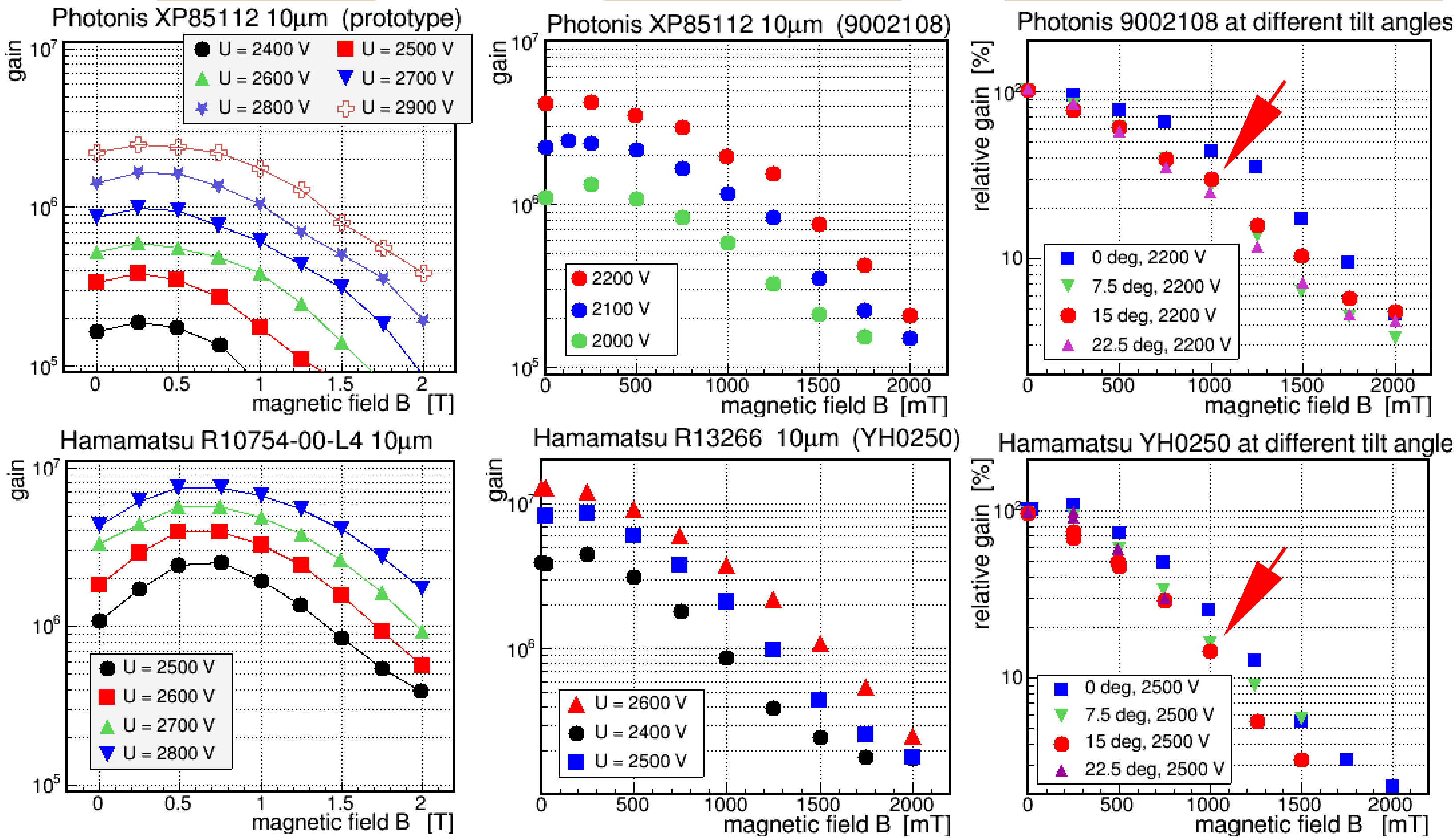


Gain of non-ALD and ALD Tubes

Non-ALD | **ALD; diff. HV** | **ALD; diff. tilt angles**

Photonis

Hamamatsu



- ALD tubes show faster gain drop in B-fields than non-ALD tubes!
  - **Photonis 9002108:** gain drop at **1 Tesla**, 0 deg: factor 2; **15 deg: factor 3**
  - **Hamamatsu YH0250:** gain drop at **1 Tesla**, 0 deg: factor 4; **15 deg: factor 6**

Properties of 2" Hamamatsu (8x8)

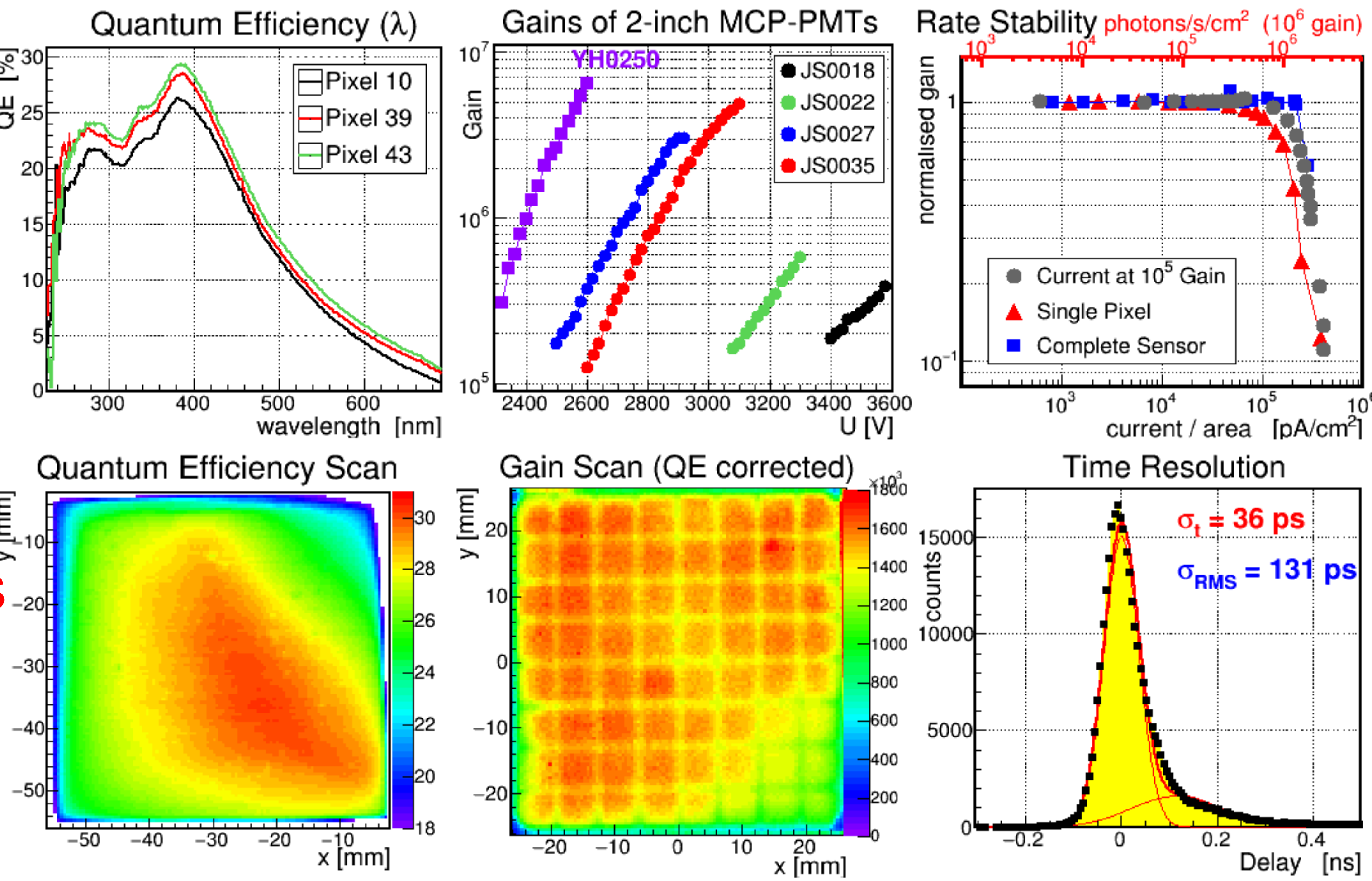
YH0250

positive

- high QE (>25%)
- lower HV needed than with first tubes
- gain homogeneity
- rate capability to ~10^6 photons/s/cm^2
- good TTS and RMS time resolution

still marginal

- QE homogeneity (~20% fluctuation)



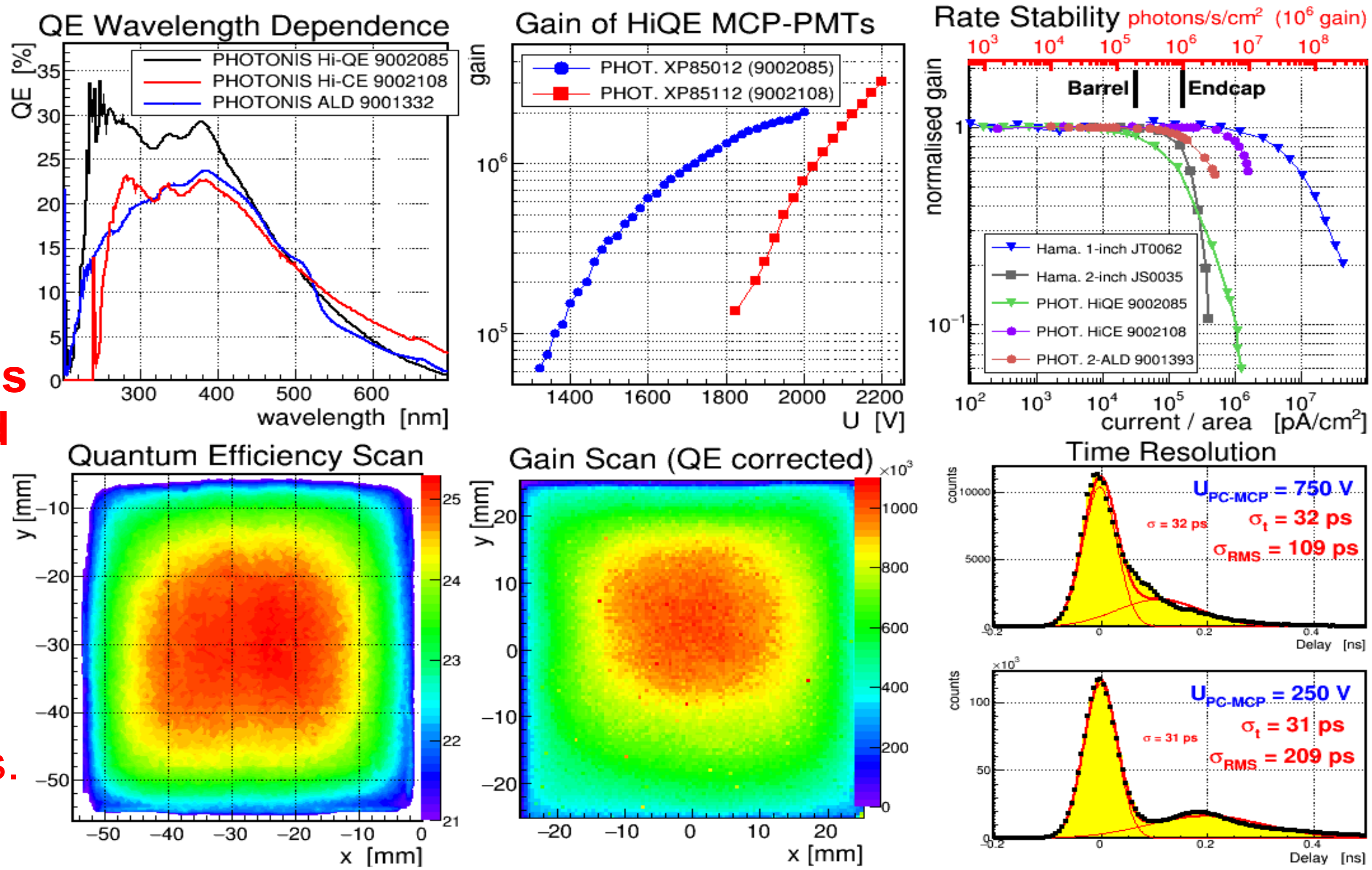
New 2" Hamamatsu MCP-PMT (R13266) without film is suitable for PANDA DIRCs in principle (lifetime pending)

Properties of hiCE Photonis (8x8)

9002108

positive

- high QE (>25%) and CE (>90%) → **DQE >20%**
- **maybe fewer tubes per sector needed**
- QE homogeneity
- low HV required
- rate capability to >>10^6 phots/s/cm^2
- good RMS time res. with higher $U_{PC\text{-}MCP}$



could be better

- gain homogeneity (x2.5 fluctuation)

New hiCE and hiQE Photonis MCP-PMT (9002108) is suitable for PANDA DIRCs (lifetime pending)

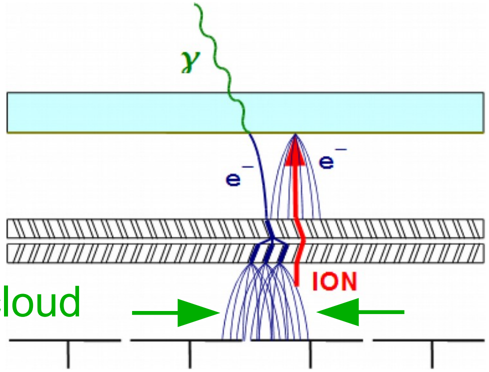
Scans with TRB/PADIWA DAQ

For details about TRB/PADIWA DAQ-system see refs. in JINST 13 (2018) C02010

- Each channel: TRB system is permanently analyzing data stream and buffering PADIWA time and time-over-threshold (ToT) information of all hits above threshold
- 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, hit time, ToT, number of hits
- Higher level information accessible:
  - **Afterpulse** distributions → TOF of feedback ions
  - **Darkcount** xy-distributions
  - Charge sharing (and electronic) **crosstalk** (>= 2 hits at same time)
  - **Recoil electron** distributions (spatial information and time delay)

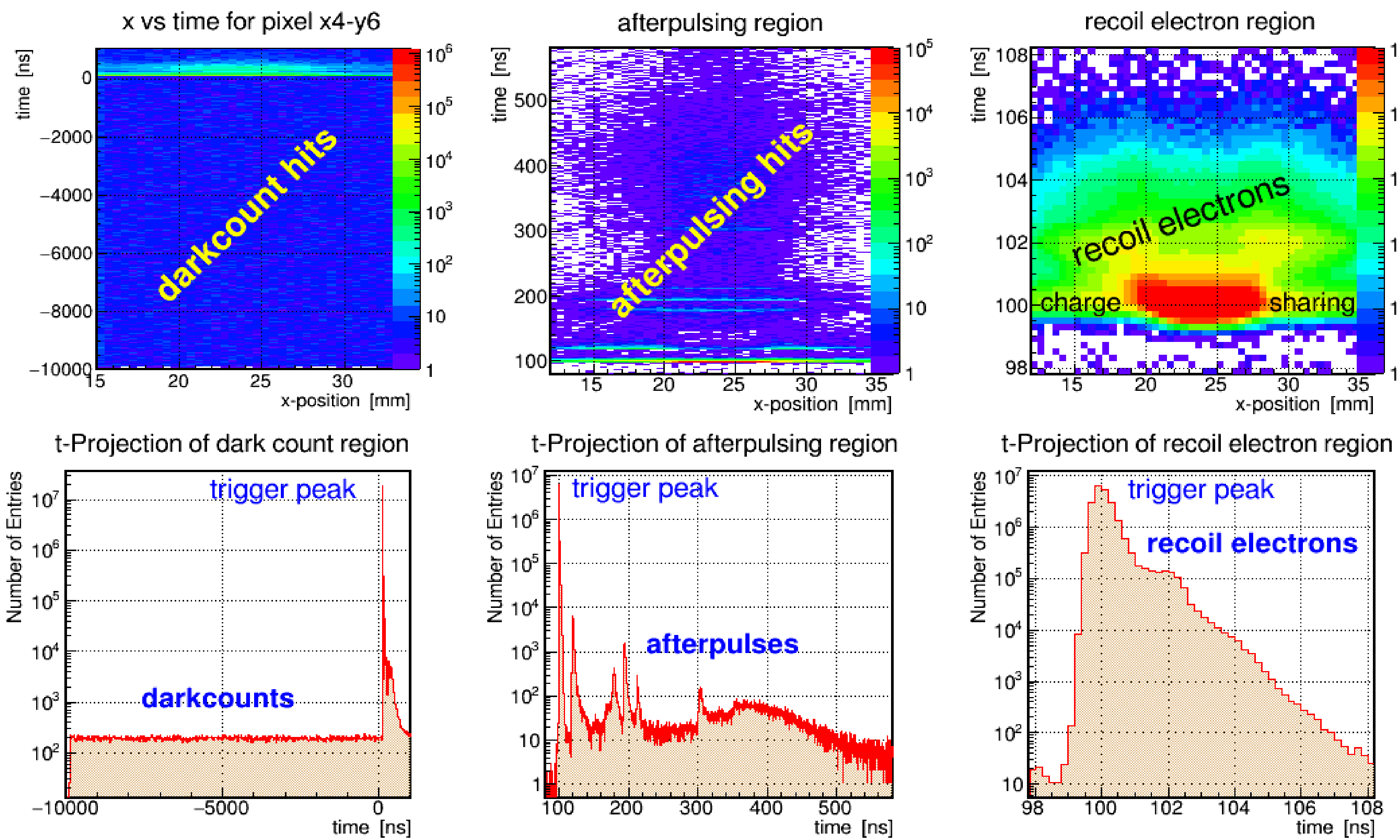
T. Gys, NDIP 2014

width of charge cloud



- TRB scans allow the **separation of**
  - **hits from recoil electrons**
  - **charge sharing events**
  - **afterpulse hits**

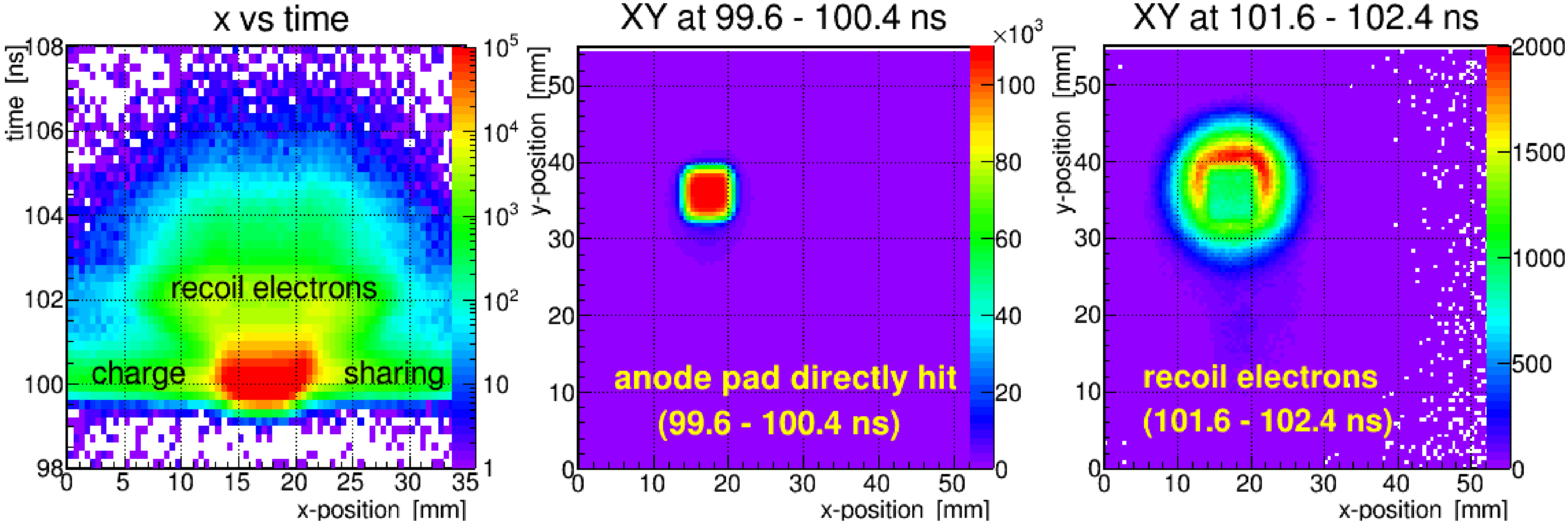
Information from TRB-Scans



PHOTONIS 9002085; read out pixel: x4-y6

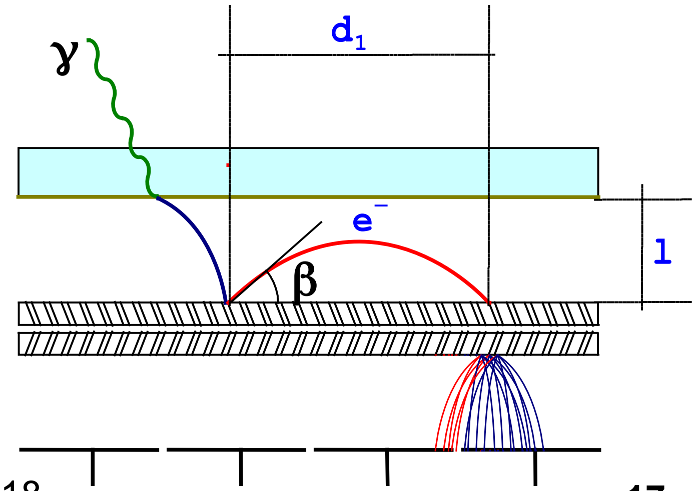
Spatial Distribution of Recoil e^-

PHOTONIS 9002085; read out pixel: x3-y6



- Prompt hits (at 100 ns) populate only the anode pad area (and electronic crosstalk)
- Later hits fill a wider spacial area (~18 mm Ø)
- Circular spacial distribution of later hits point to recoil electrons

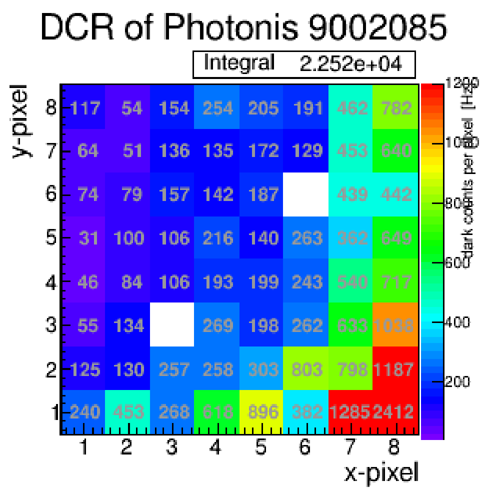
NIMA595 (2008) 169

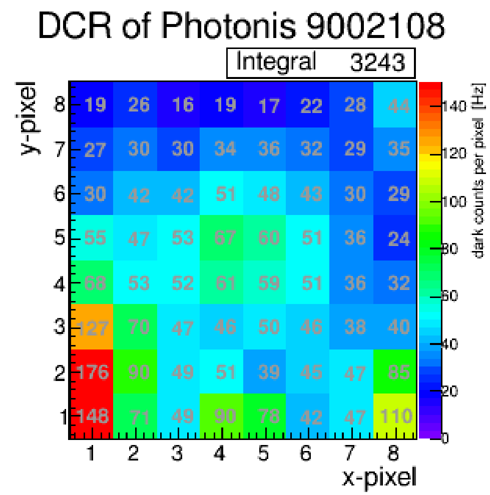


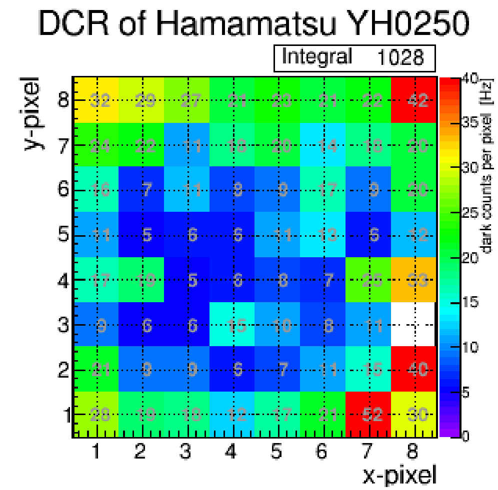
Comparison of Darkcount Rates

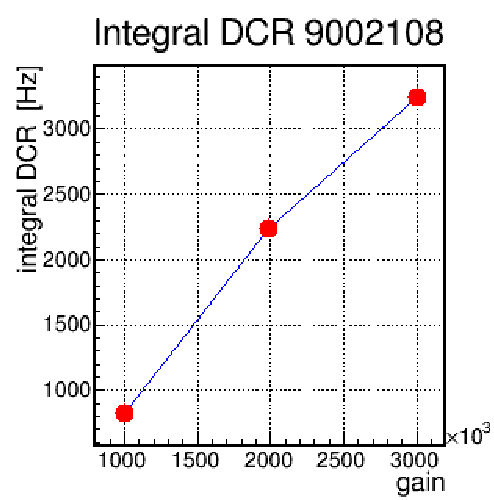
DCR determined by integral between N(-10µs) to N(0µs)

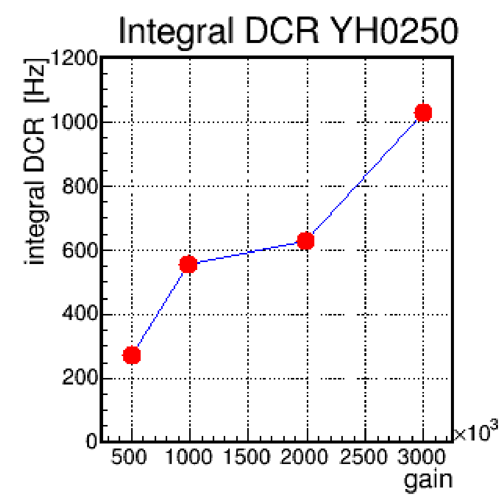
- 15 mV threshold (corresponding to ~1/3 mean pulse height for 1 p.e.)
- Highest integral DCR (>20 kHz) with 25 µm non-ALD Photonis 9002085
- Lowest integral DCR (<1 kHz) with 10 µm ALD Hamamatsu YH0250
- Rate/pixel is not homogeneously distributed
- DCR increases with gain









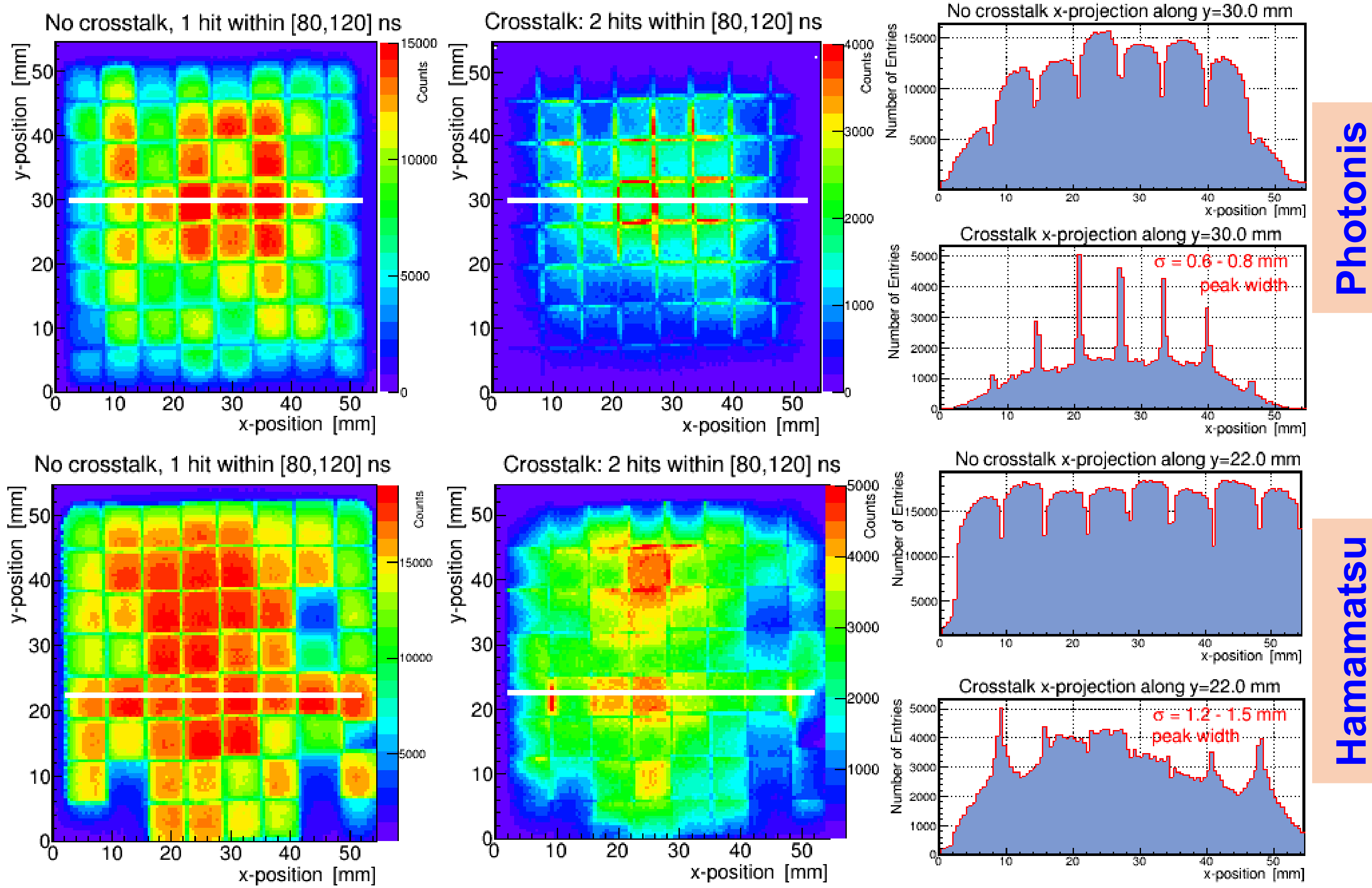


Highest darkcount rates usually seen in corner or edge pixels
→ reason currently unknown !

Comparison of Crosstalk

Crosstalk can be determined by a cut around t = 80 to 120 ps

- 1 hit distribution → anode grid
- 2 hit distribution → crosstalk by charge sharing
- Determination of charge cloud size possible (could be also size of induction region)

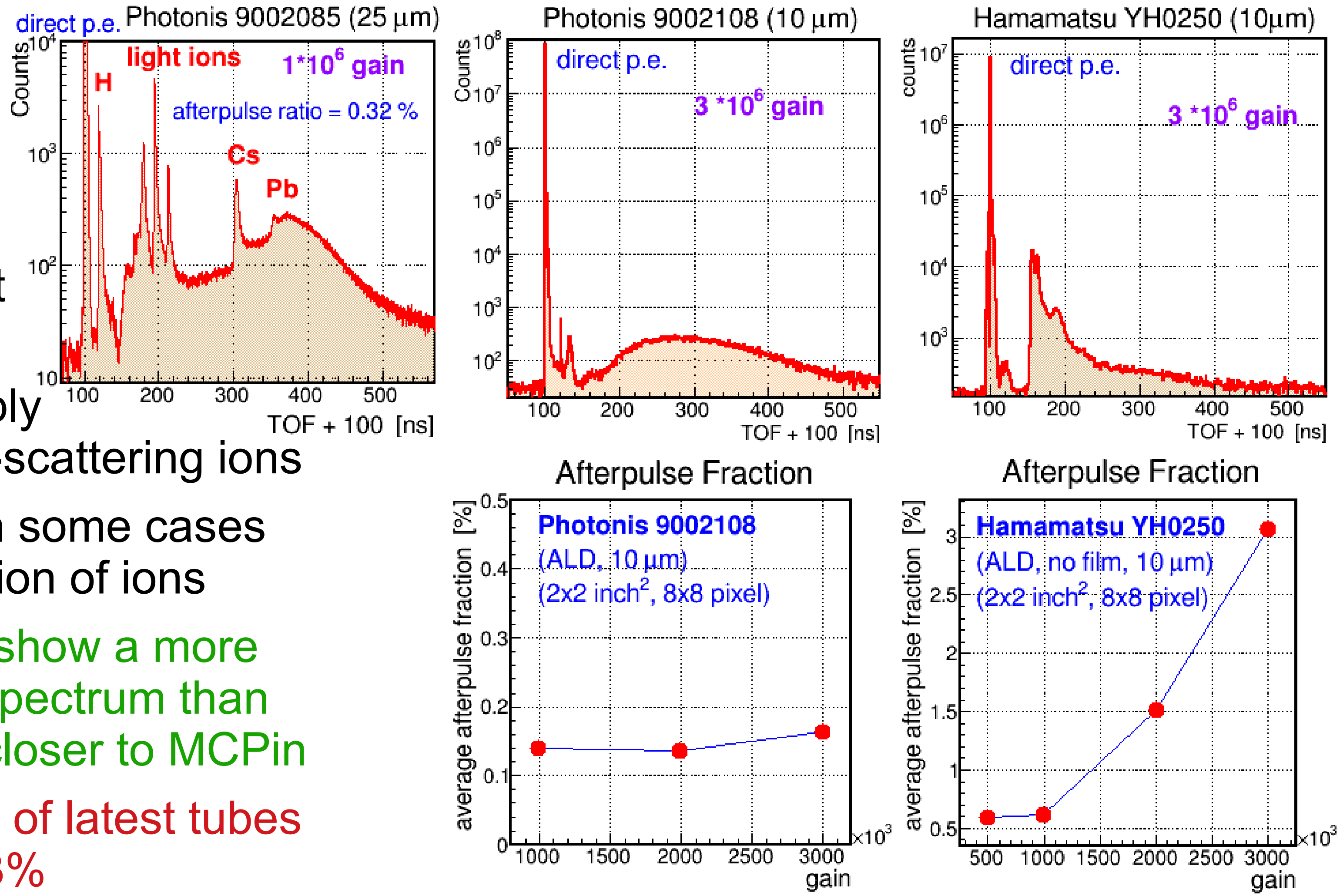


Hamamatsu MCP-PMT shows different crosstalk behavior than Photonis → probably caused by different (MCP – anode) distance

Comparison of Afterpulses

Measure afterpulse TOF distributions and fractions

- Laser pulse peak at (direct p.e.) 100 ns
- Large bump probably caused by multiple-scattering ions
- TOF distributions in some cases allow the identification of ions
- Hamamatsu tubes show a more compressed TOF spectrum than Photonis → PC is closer to MCPin
- Afterpulse fractions of latest tubes vary from 0.1% to 3%

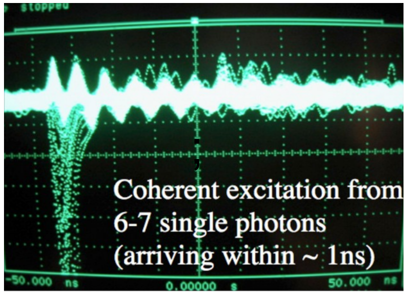


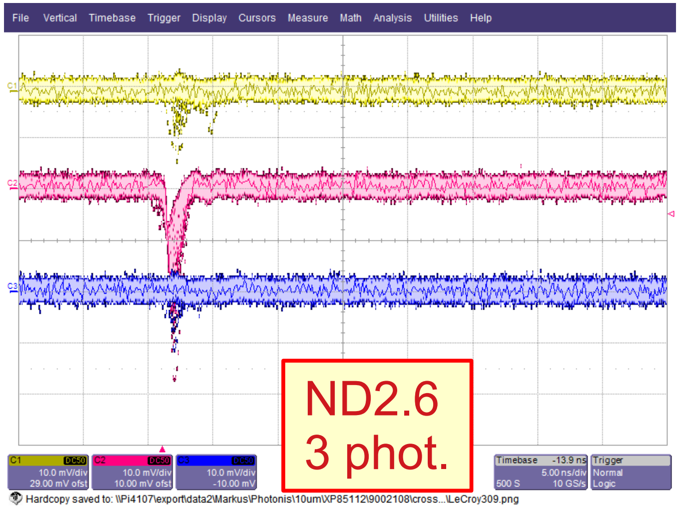
No gain dependence seen in afterpulse fractions of Photonis MCP-PMTs, this is different for Hamamatsu tube

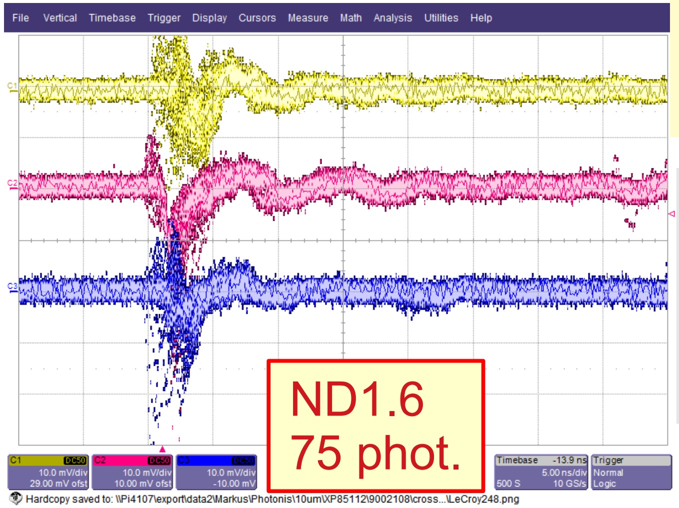
Problem: Signal Oscillations

RICH 2016: J. Vav'ra, NIM A876 (2017) 185

- J. Vav'ra: "coherent excitations" in old (2005) Planacon tubes
- Recently tested with latest MCP-PMTs:
  ALD coating; 10^6 gain; diffuse **illumination of full PC area**







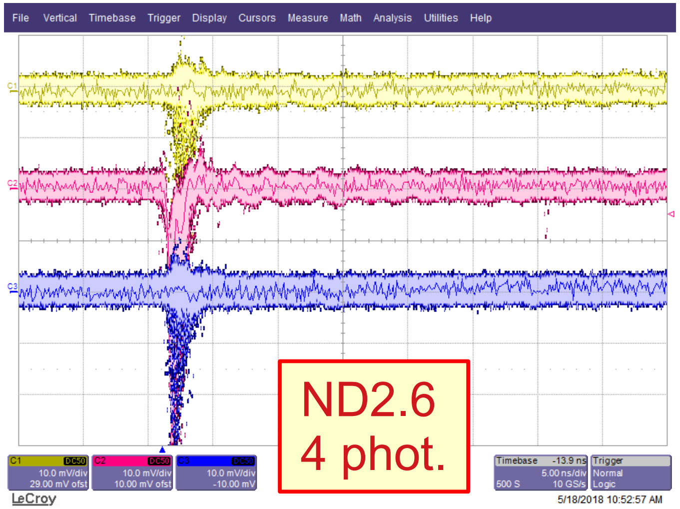
Photonis 9002108

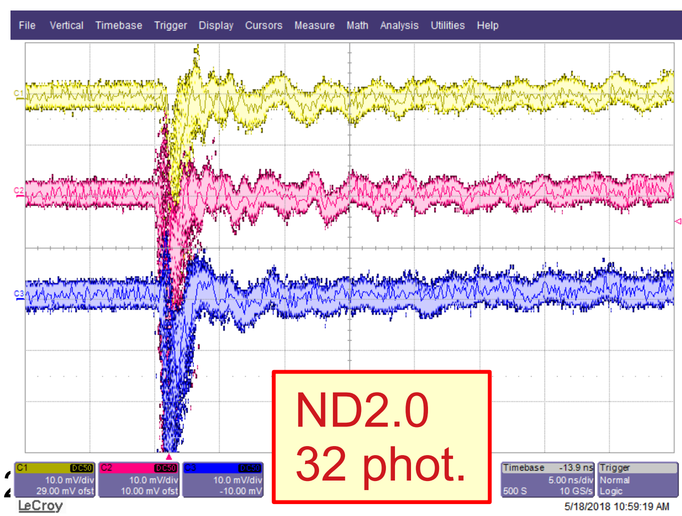
x: 5 ns/div
y: 10 mV/div

Trigger:
Laser * px44

pixel's read out

11	12	13	14	15	16	17	18
21	22	23	24	25	26	27	28
31	32	33	34	35	36	37	38
41	42	43	44	45	46	47	48
51	52	53	54	55	56	57	58
61	62	63	64	65	66	67	68
71	72	73	74	75	76	77	78
81	82	83	84	85	86	87	88





Hamamatsu YH0250

x: 5 ns/div
y: 10 mV/div

Trigger:
Laser * CH29

pixel's read out

CH8	CH7	CH6	CH5	CH4	CH3	CH2	CH1
CH16	CH15	CH14	CH13	CH12	CH11	CH10	CH9
CH24	CH23	CH22	CH21	CH20	CH19	CH18	CH17
CH32	CH31	CH30	CH29	CH28	CH27	CH26	CH25
CH40	CH39	CH38	CH37	CH36	CH35	CH34	CH33
CH48	CH47	CH46	CH45	CH44	CH43	CH42	CH41
CH56	CH55	CH54	CH53	CH52	CH51	CH50	CH49
CH64	CH63	CH62	CH61	CH60	CH59	CH58	CH57

Findings from Oscillation Effect

- We see a similar oscillation effect in the latest PHOTONIS MCP-PMTs as observed by Jerry >10 years ago with Burle Planacons
- Measured pulse distributions and pulse height spectra for different
  - ND filters (→ number of photo electrons per pixel)
  - number of illuminated pixels (→ number of photo electrons per sensor)
- Quantitative results
  - full sensor illuminated:
    - oscillation starts at ~10 single photons (per sensor)
    - significant increase of oscillations with more photons (per sensor)
  - effect seen in the latest 2-inch of PHOTONIS and Hamamatsu MCP-PMTs
- Oscillation is also visible without a backplane attached to the tube
- Why does this matter?
  - **may cause worse time resolution**
  - **fake hits in anode pixels**

Summary and Outlook

- Summary
  - Best MCP-PMTs show **lifetimes up to 20 C/cm²**
    → new ALD technique brought **x100 lifetime improvement**
  - Recent 2-inch MCP-PMTs show very favorable properties (e.g., high QE, high CE, low DCR, good rate capability, …),
    but **ALD coated MCP-PMTs are more sensitive to strong B-fields**
  - PADIWA/TRB DAQ allows investigation of internal MCP properties
  - Signal oscillation problems when several pixels are hit simultaneously
- Outlook
  - Tendering process for MCP-PMTs will start very soon
  - Semi-automatic quality assurance setup is available to simultaneously measure most (wanted and unwanted) properties of many MCP-PMTs
  - Growing data base should give more insight into MCP-PMT features

Illumination Overview

	Sensor ID	Integral charge (July 10, 2018) [mC/cm^2]	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	**15909**	22.96	8.16	**36%**	Start: 12 Dec. 12 Stop: 26 Oct. 17
	9001393	**19988**	19.05	19.68	**103%**	Start: 23 Jan. 14 ongoing
Hamamatsu R10754X	KT0001 (M16M)	**20090**	21.52	5.20	**24%**	Start: 20 Aug. 13 Stop: 10 Jul. 18
	KT0002 (M16M)	**19334**	21.4	5.17	**24%**	Start: 21 Oct. 13 Stop: 10 Jul. 18
Hamamatsu R13266	JS0018 (M768)	**1284**	17.97	2.55	**14%**	Start: 31 Aug. 16 Stop: 10 Jul. 18
	JS0022 (M64)	**4918**	17.43	4.46	**26%**	Start: 11 Dec. 15 Stop: 5 Apr. 18
	JS0027 (M768)	**2756**	24.27	23.00	**95%**	Start: 31 Aug. 16 ongoing
	JS0035 (M64)	**7512**	25.47	25.28	**99%**	Start: 31 Aug. 16 ongoing
	YH0250 (M64M)	**986**	25.37	25.47	**100%**	Start: 5 Apr. 18 ongoing