Tremendously Increased Lifetime of MCP-PMTs

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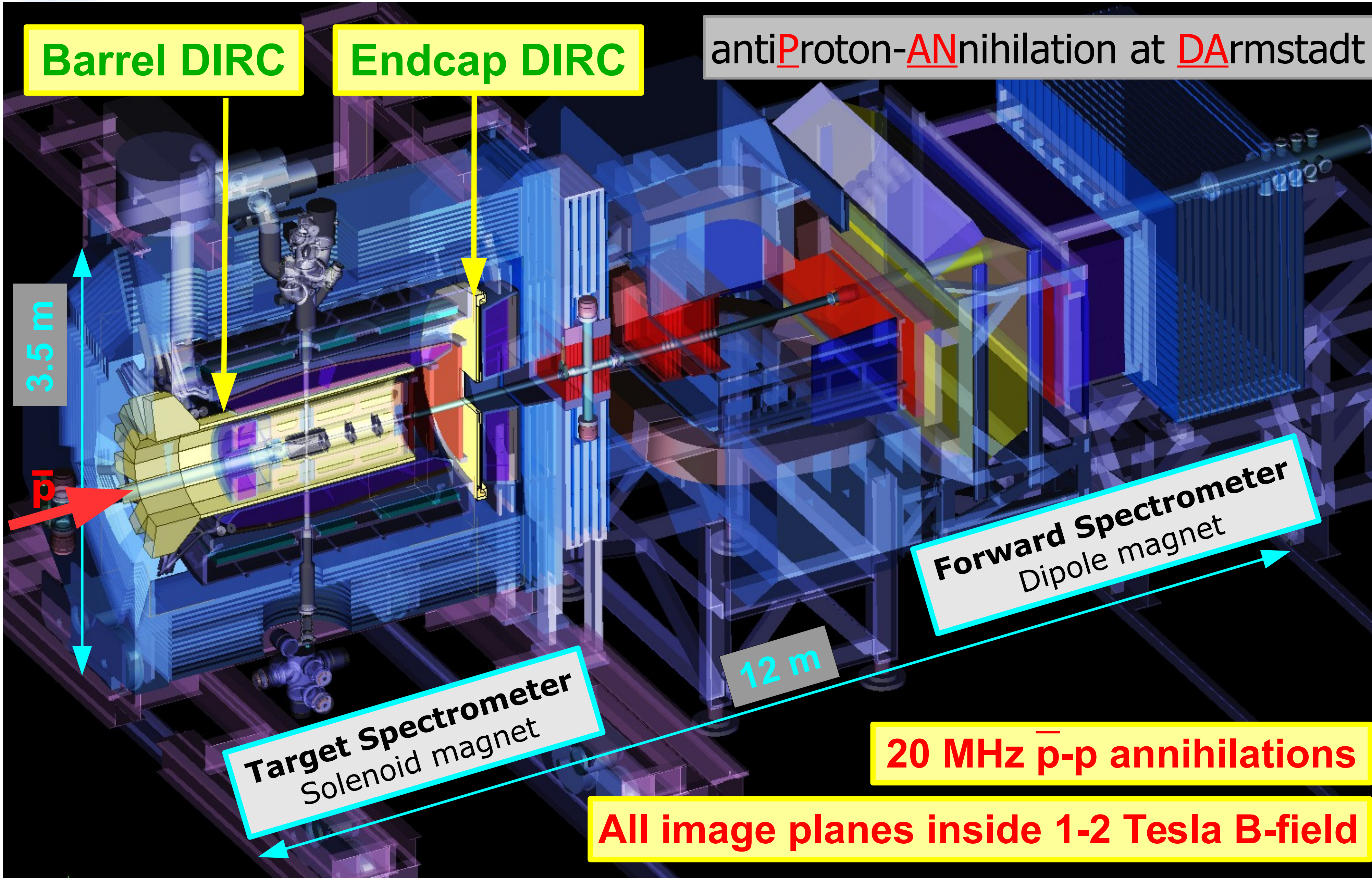
for the PANDA Cherenkov Group

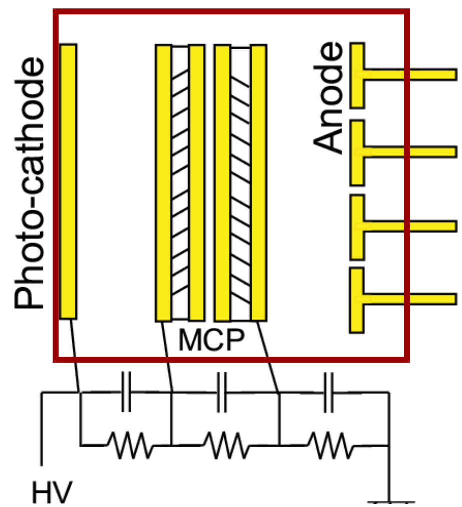
- Introduction and motivation
- Approaches to increase lifetime
- Results of aging tests
- Outlook and summary

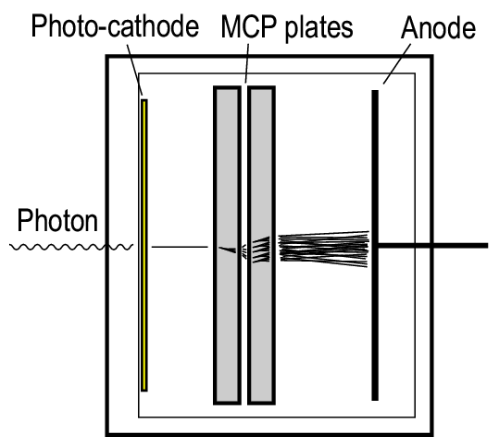
$\overline{\text{P}}$ANDA Detector at FAIR

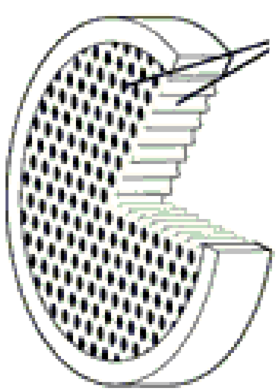


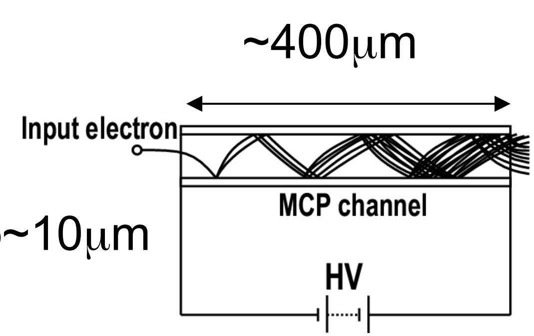
Microchannel-Plate PMT

electron multiplication in glass capillaries (∅ ≈ 10-25 μm)









- usable in high magnetic fields
- high gain:
  - $>10^6$ with 2 MCP stages
  - single photon sensitivity
- very fast time response:
  - signal rise time = 0.3 – 1.0 ns
  - TTS < 50 ps
- low dark count rate
- quantum efficiency comparable to that of standard vacuum PMTs
- multi-anode PMTs available
- caveats:
  - lifetime (QE drops)
  - price

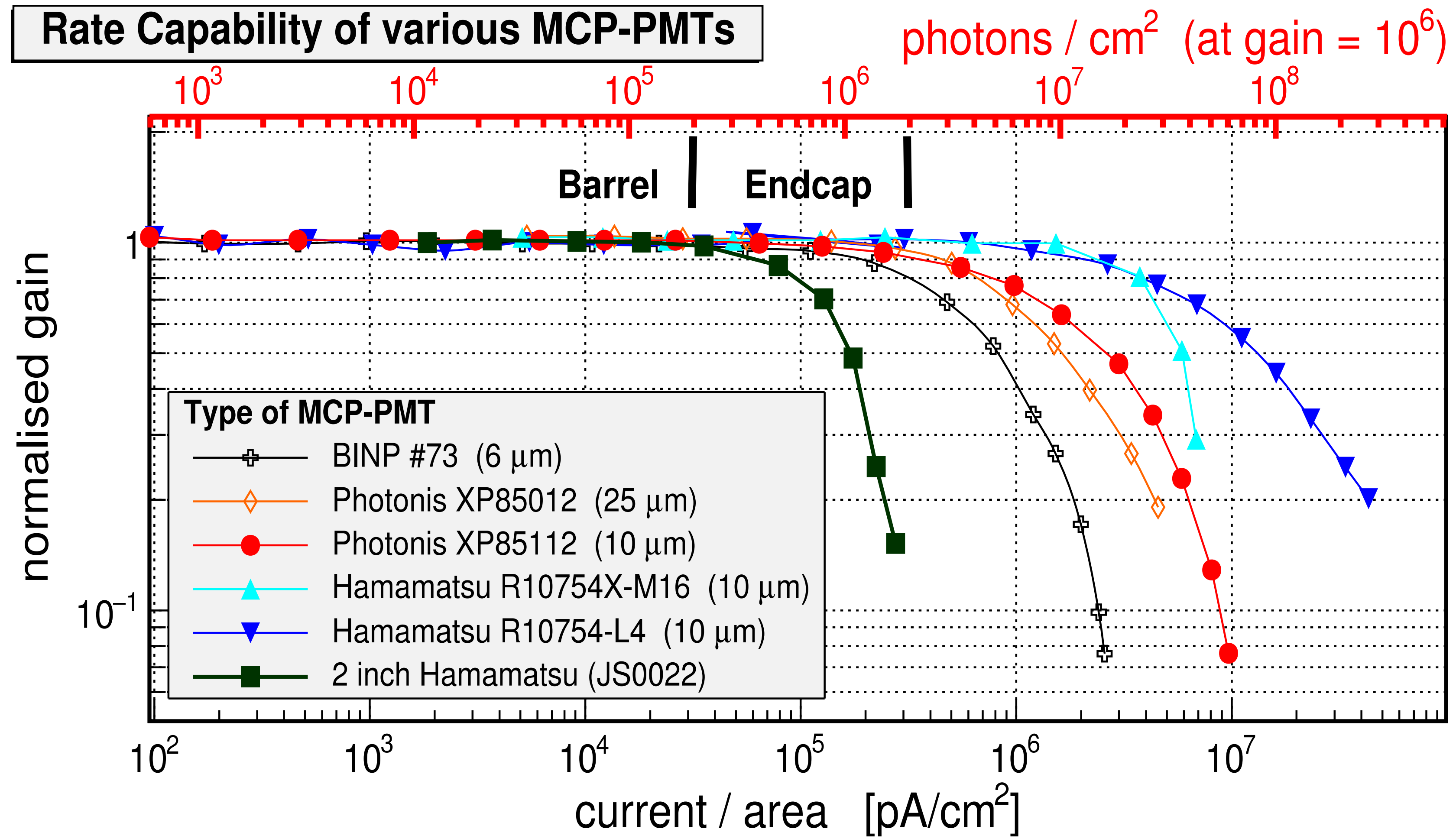
Rate Estimates for PANDA

- **rate capability and lifetime are the most critical issues** for the application of MCP-PMTs in any high-rate experiment
- expected rates and anode charges of the PANDA DIRCs:

	total rate	anode rate (after Q.E.)	integrated anode charge / year	integrated anode charge / 10 years
	[MHz/cm^2]	[MHz/cm^2]	[C/cm^2/year] at 10^6 gain (at 100% dc)	[C/cm^2] at 10^6 gain (at 50% duty cycle)
Barrel DIRC				
at end of radiator	*60*	*5.6*	*28*	
at readout plane	1.7	**0.2**	**1**	**5**
Endcap DIRC				
at rim of radiator	*19*	*2*	*10*	
focussing	7.5	**0.8**	**4**	**20**

- Endcap DIRC with much higher photon rate than Barrel DIRC
  → **wavelength band filter to reduce photon rate to 5 C/cm^2**

Rate Capability

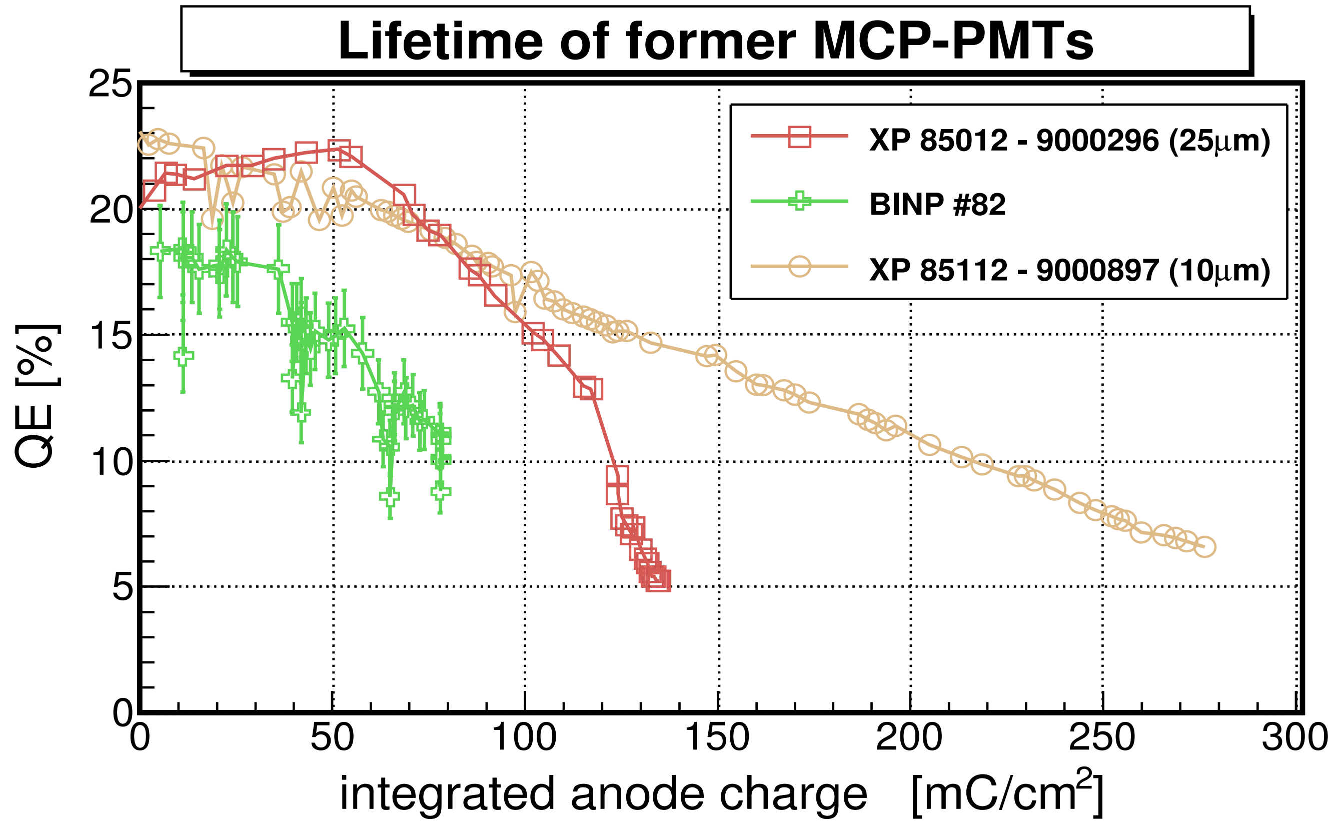


- most MCP-PMTs show stable operation to ~200-300 kHz/cm^2 single photons (at gain 10^6)
- many recent MCP-PMT models stable up to >1 MHz/cm^2

Lifetime of former MCP-PMTs

Status ~4 years ago

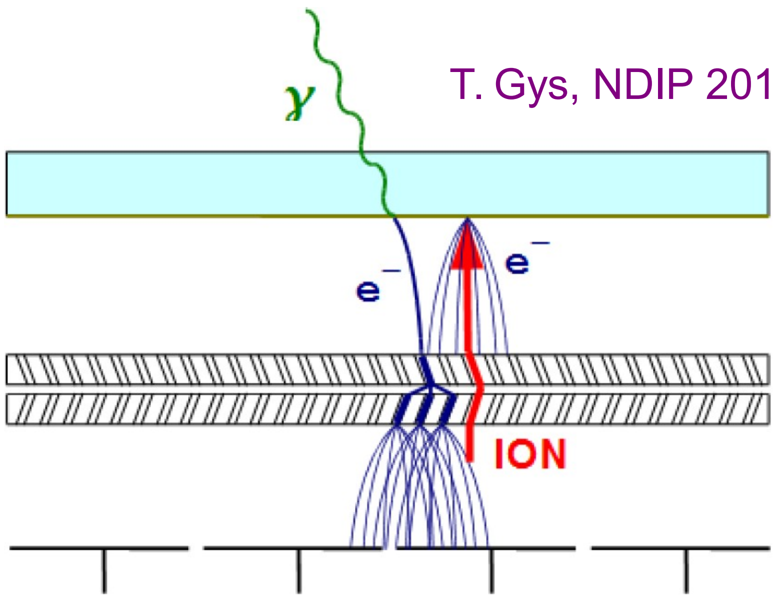
- BINP with Al_2O_3 film at MCP entrance to stop feedback ions
- PHOTONIS with improved vacuum and electron scrubbing of surfaces



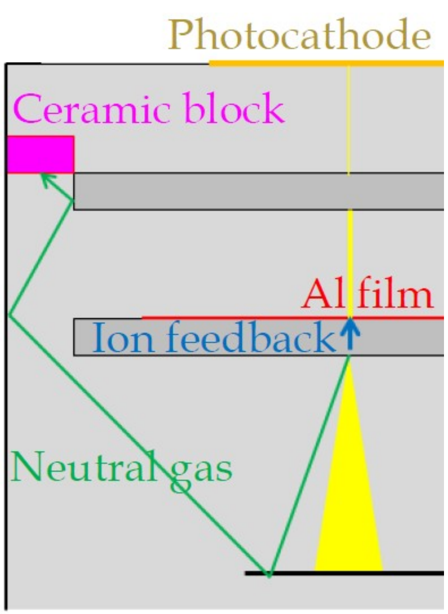
- Quantum efficiency reduced by 50% or more at <200 mC/cm^2
- By far not sufficient for PANDA

Possible Cause of MCP Aging

- 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
  - Ions accelerated towards photo cathode
    - Production of secondary pulse
    - Ions may react with PC
    - PC gets damaged and work function may gradually change
    - Degradation of Quantum efficiency (QE)
- Neutral molecules from residual gas
  - Passing between MCPs and walls
  - CO_2, O_2 and H_2O react with PC



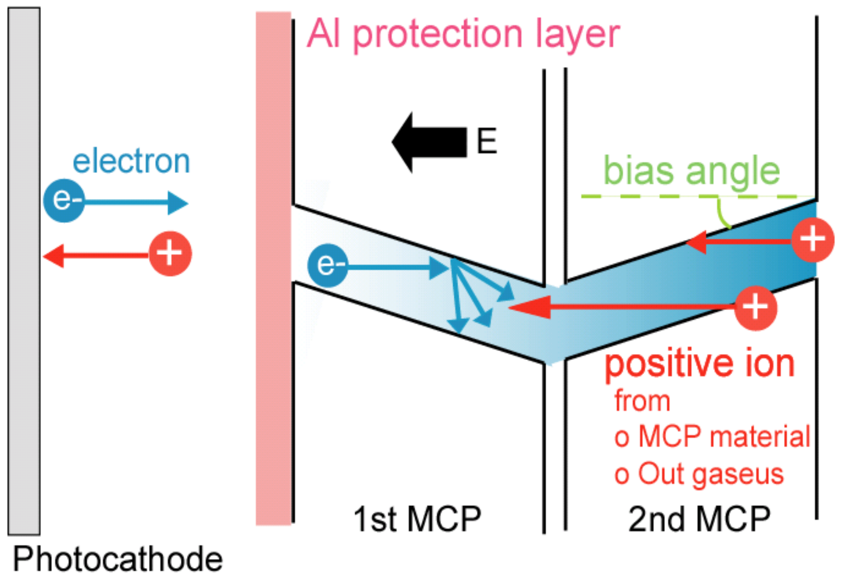
T. Gys, NDIP 2014



K. Matsuoka, RICH 2013

First Approaches to Reduce Aging

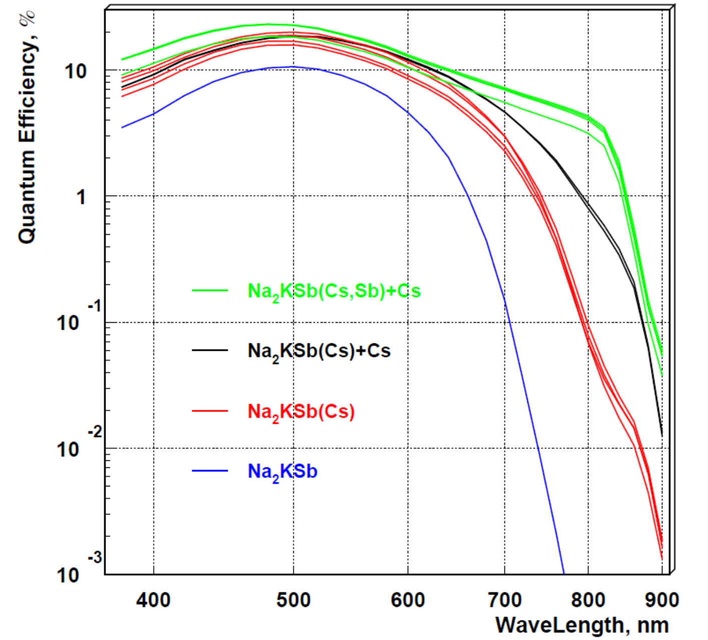
- Stop feedback ions by thin Al_2O_3 film (5-10 nm)
  - In front of first MCP layer (older BINP and first Hamamatsu tubes)
    - disadvantage: another reduction of collection efficiency (CE) by about 1/3
  - Later between MCP layers (second generation Hamamatsu tubes)
    - no CE reduction but higher HV needed

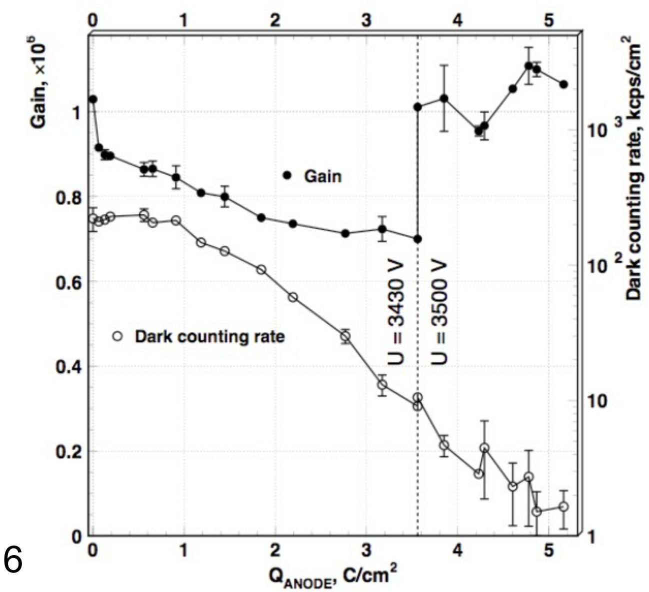


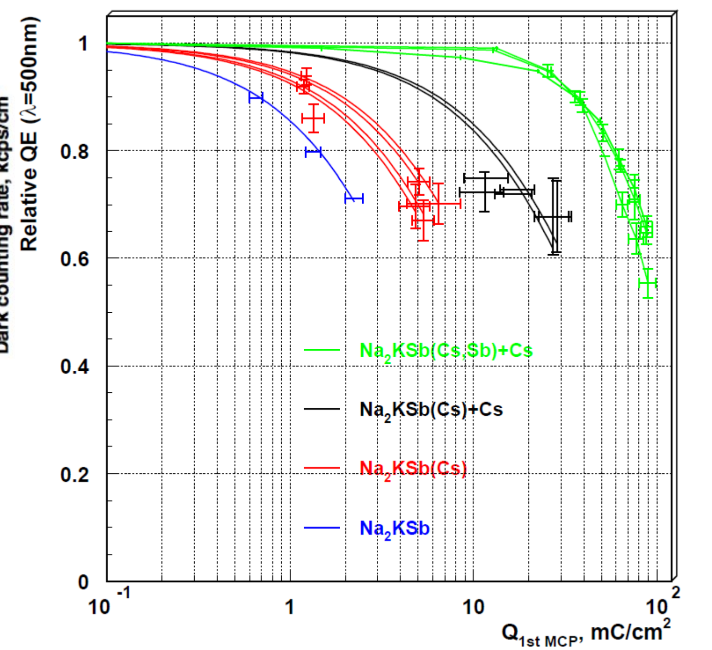
- Improve vacuum quality
- Improved cleaning of MCP surfaces
  - Electron scrubbing (older PHOTONIS and latest BINP tubes)
- Prevent neutral molecules in anode region from reaching the PC
  - Anode region is hermetically sealed from PC region (2^{nd} gen. Hamamatsu)
    - [NIM A629 (2011) 111]

Production of more Robust PC

- MCP-PMTs developed at BINP for FARICH
  - without protection layer
  - with heavy electron scrubbing
- New photo cathode [JINST 6 C12026 (2011)]
  - Na_2KSb: DCR < 0.5 kHz/cm²
  - $Na_2KSb(Cs)$: DCR = 0.5 kHz/cm²
  - $Na_2KSb(Cs)$ + Cs: DCR = 5 kHz/cm²
  - $Na_2KSb(Cs)$ + Cs_3Sb: DCR = 50-100 kHz/cm²
- Gain recoverable
- Exponential reduction of dark count rate (DCR)
- Slower QE degradation



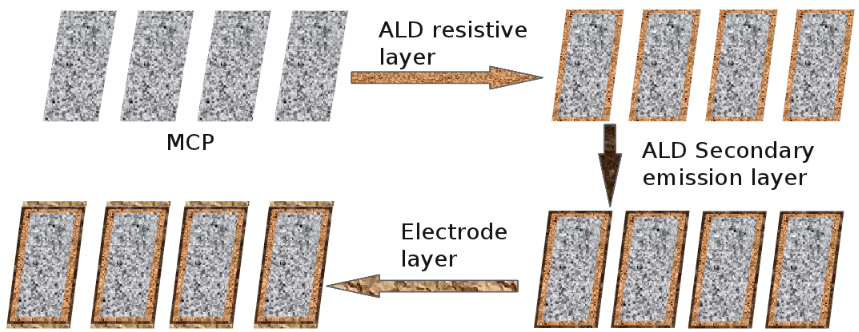


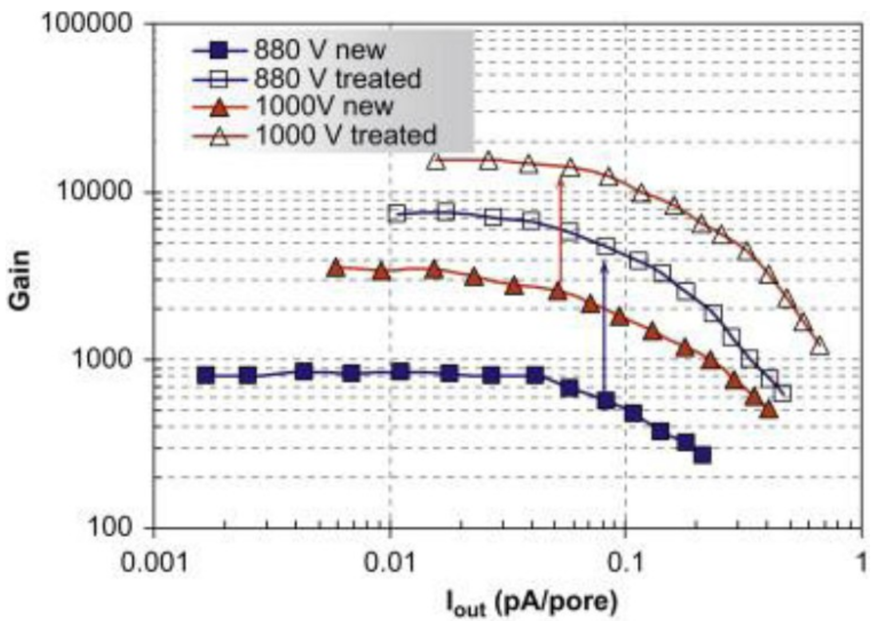


Atomic Layer Deposition (ALD)

- 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, ...
- Possibility to use MCP substrates other than lead glass
  - e.g., borosilicate glass
    - higher bake-out temperature possible
    - fewer desorption during MCP operation

[NIM A639 (2011) 148]

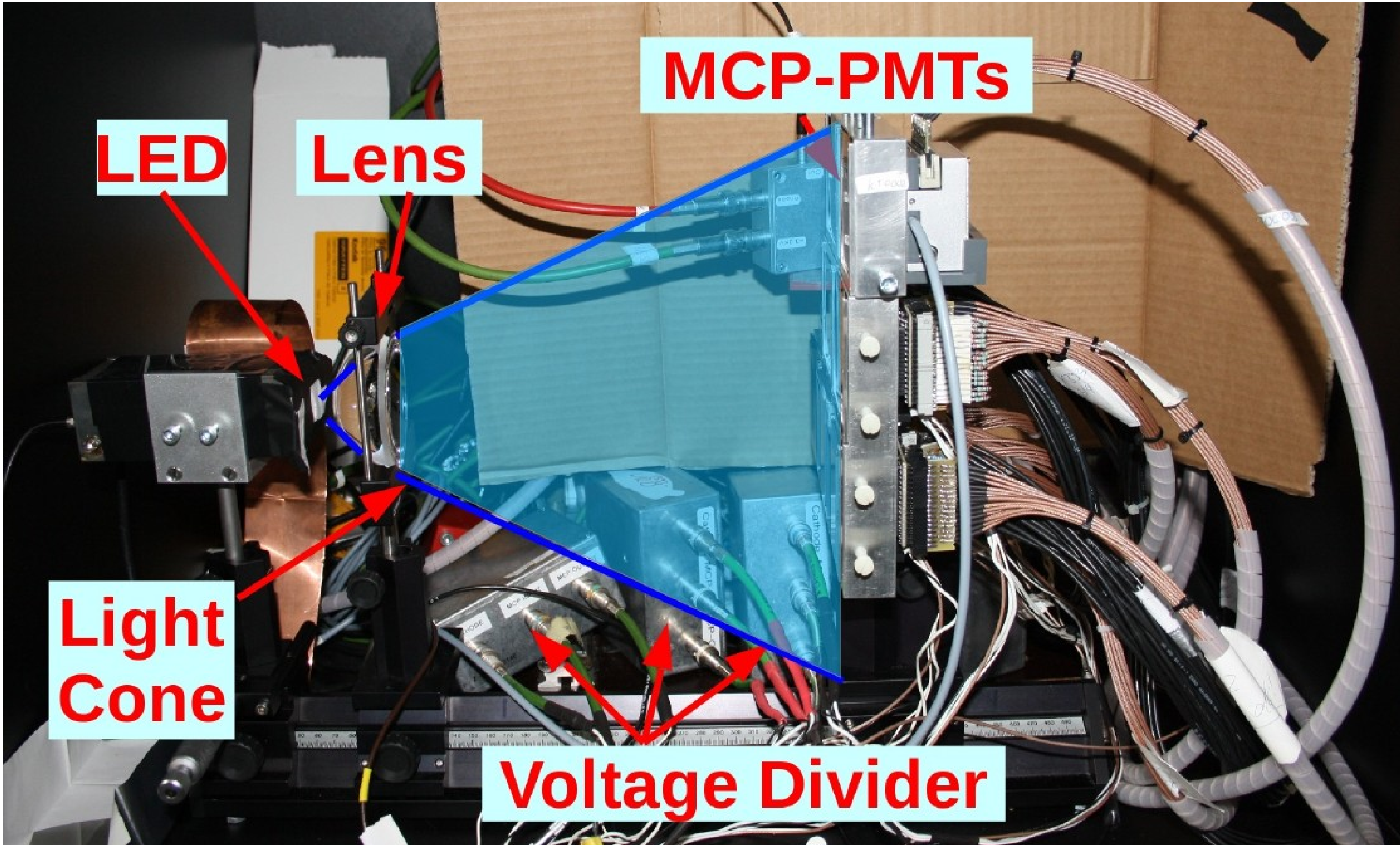




Simultaneous Aging of MCP-PMTs

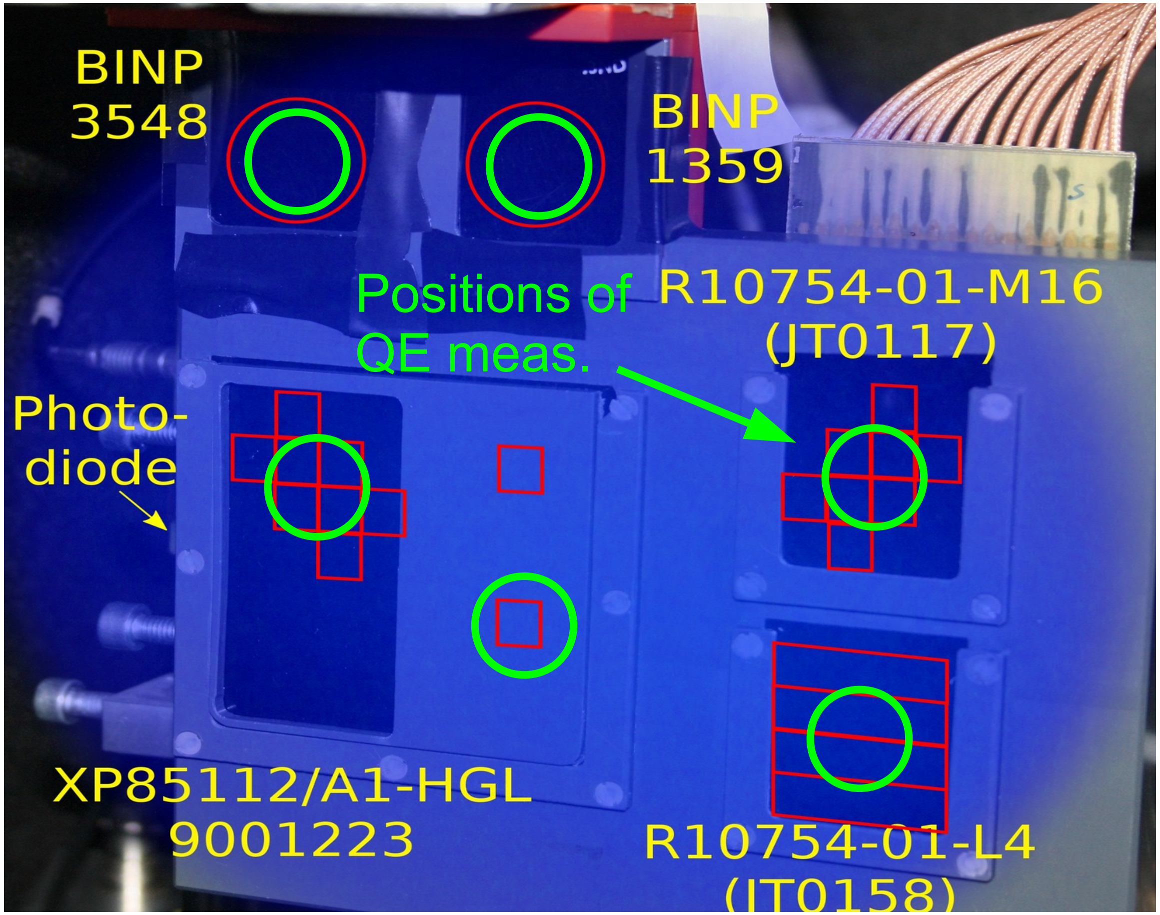
- **Problem in 2011:** The few aging tests existing were done in rather different environments → results are difficult to compare
- **Goal:** measure aging behavior for all available lifetime-enhanced MCP-PMTs in same environment
- **Simultaneous illumination** with common light source → same rate
- MCP-PMTs included in aging tests of last 4 years:
  - 2x BINP
    - improved vacuum and scrubbed surfaces + new photo cathode (both finished)
  - 4x Hamamatsu R10754X (1x1 inch^2)
    - L4 and M16: protection layer (film) between 1st and 2nd MCP (both finished)
    - 2x M16M: ALD technique applied (+ film between MCPs) (started end 2013)
  - 3x PHOTONIS XP85112 (2x2 inch^2)
    - 1-layer ALD surfaces (2x) and 2-layer ALD surfaces (1x, started Jan. 2014)
    - surface half covered during illumination (except 2-layer ALD tube)
  - 1x Hamamatsu R13266 (2x2 inch^2) with ALD and film (started Dec. 2015)

Illumination Setup



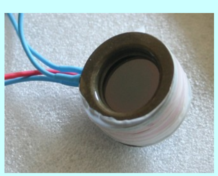
Measurement of MCP Lifetime

- Continuous illumination
  - 460 nm LED at 0.25 to 1 MHz rate attenuated to single photon level → 3 to 20 mC/cm^2/day
- Permanent monitoring
  - MCP pulse heights and LED light intensity
- Q.E. measurements
  - 250–700 nm wavelength band with monochromator Δλ = 1 nm
  - Every 2-3 weeks (at beginning days): wavelength scan
  - Every 3-4 months (at beginning weeks): complete surface scan



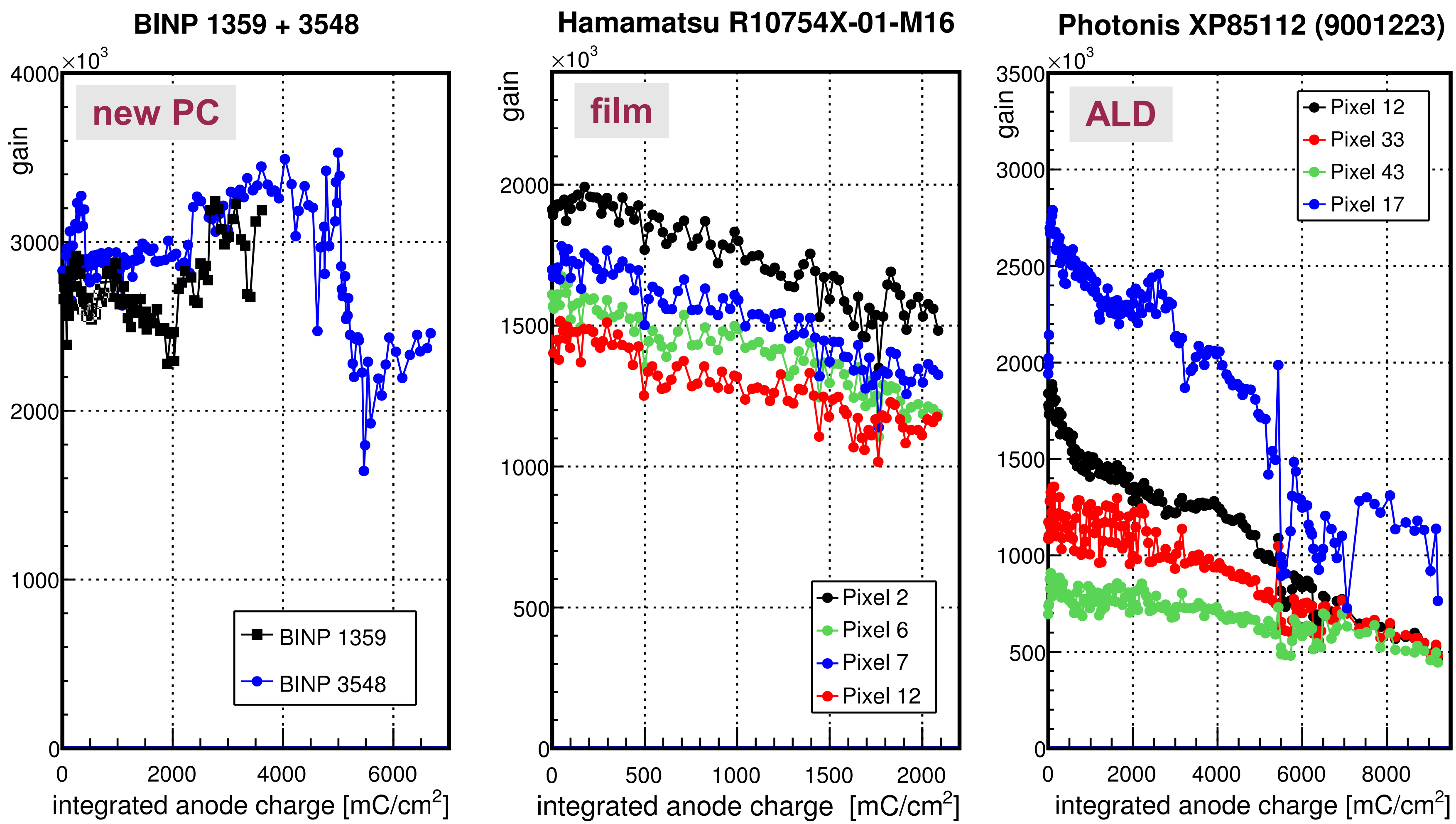
Lifetime-Investigated MCP-PMTs

	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**	**1**



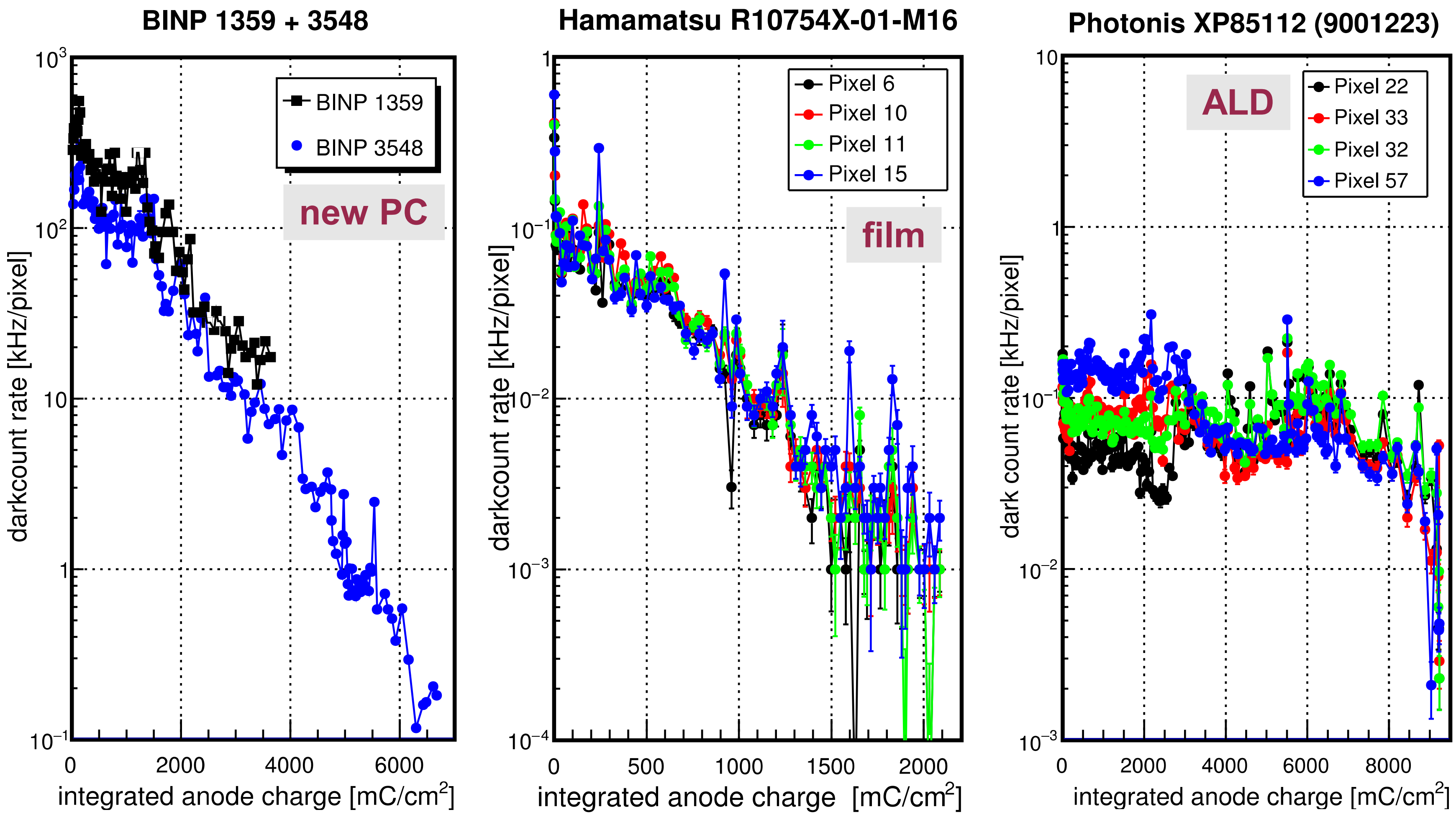
- Tubes first measured with no significant lifetime improvements
- Lifetime improved tubes measurement started ~4 years ago
- Hamamatsu 1 inch ALD tubes measurement started ~2 year ago
- Hamamatsu 2 inch ALD tube just started

Gain vs. Integrated Anode Charge



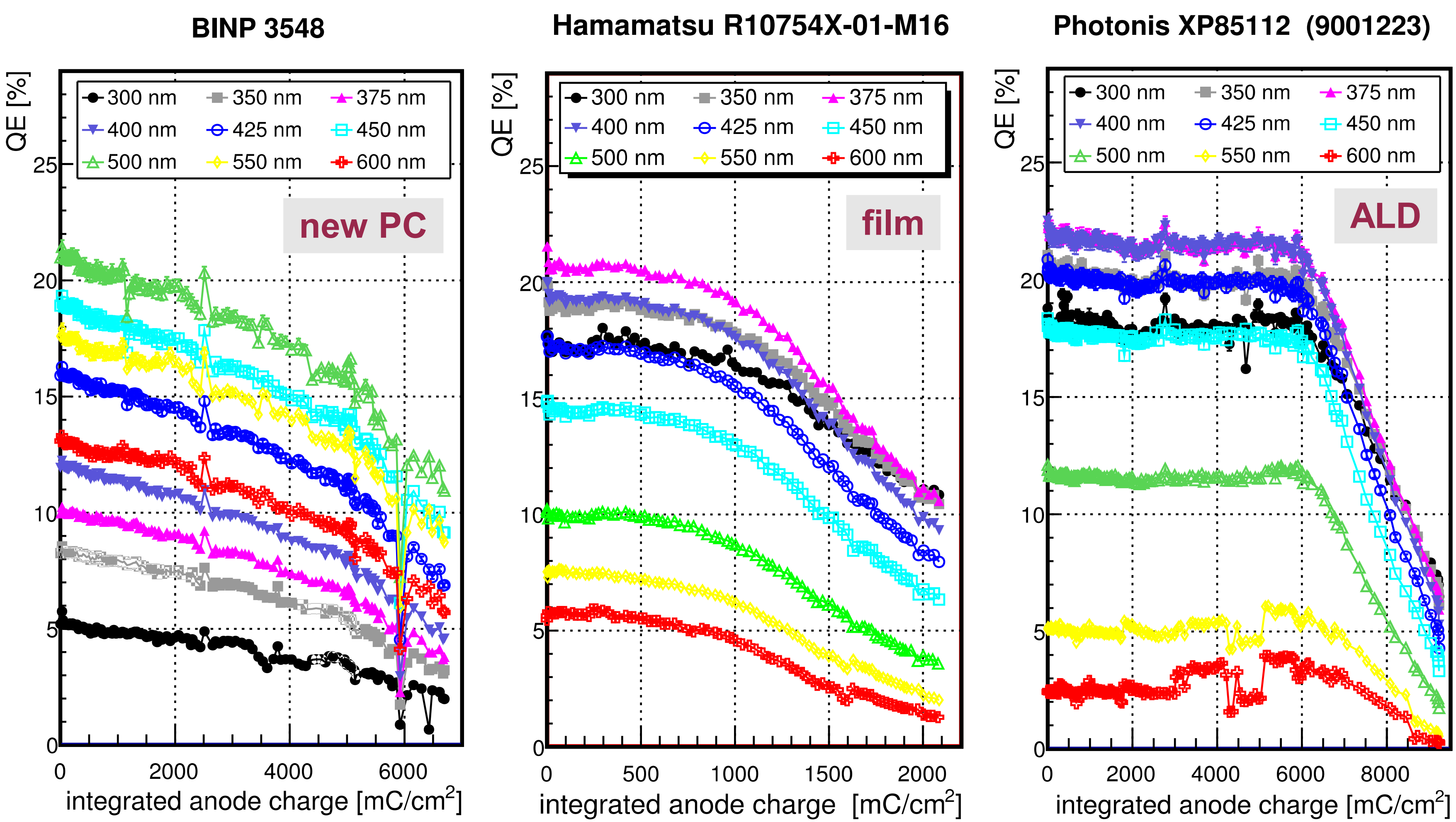
- Only moderate gain changes (except for PHOTONIS)
- This was quite different in the former MCP-PMTs !

Darkcount vs. Anode Charge



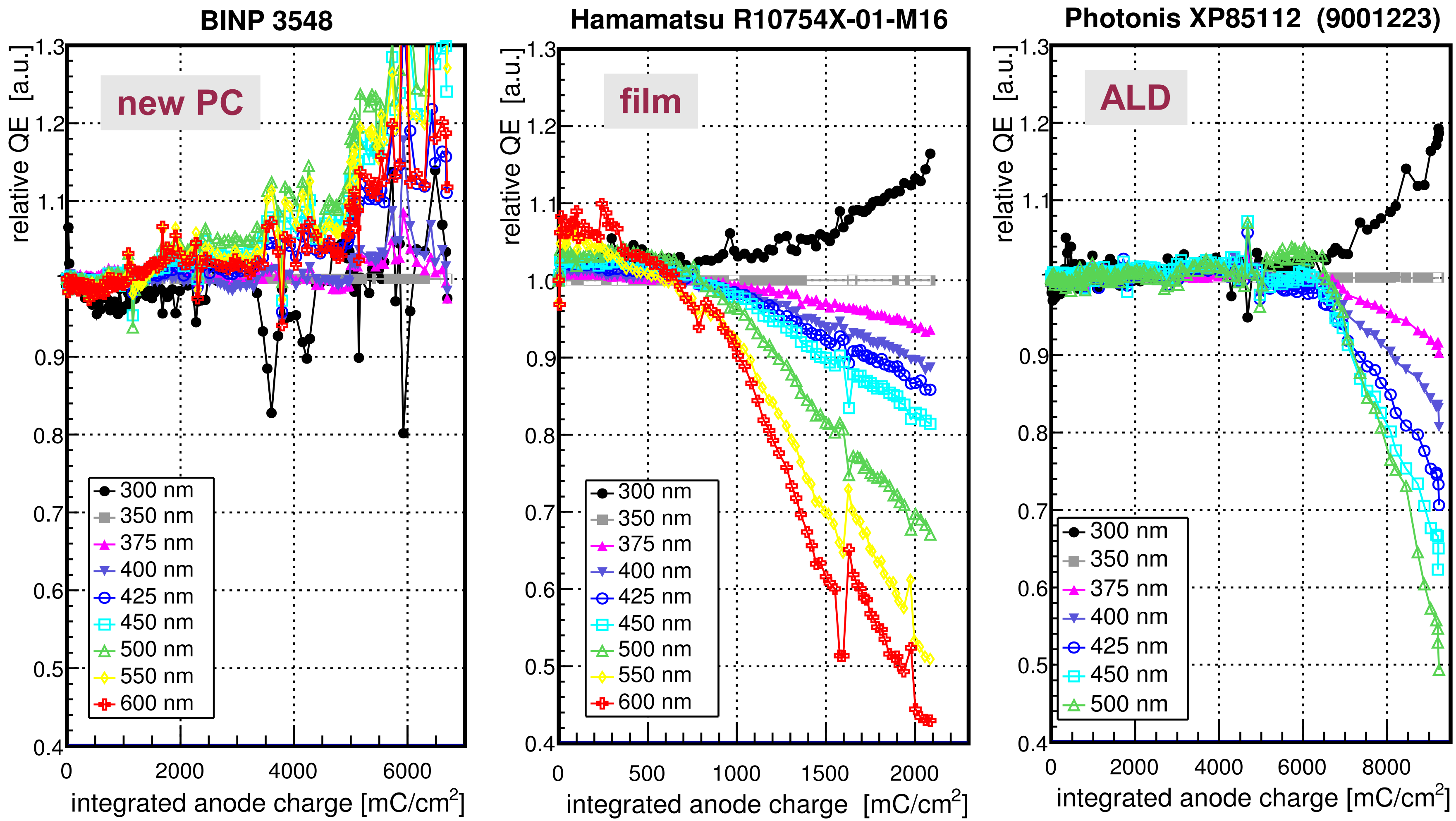
- Big exponential reduction in BINP and Hamamatsu R10754X
- Darkcount rate of PHOTONIS XP85112 (ALD) almost constant

Q.E.(λ) vs. Integral Anode Charge



- BINP new PC: continuous Q.E. degradation
- Hamamatsu film: Q.E. drops significantly above ~1 C/cm^2
- **PHOTONIS ALD: Q.E. degradation after 6 C/cm^2**

Relative Q.E.(λ) vs. Anode Charge

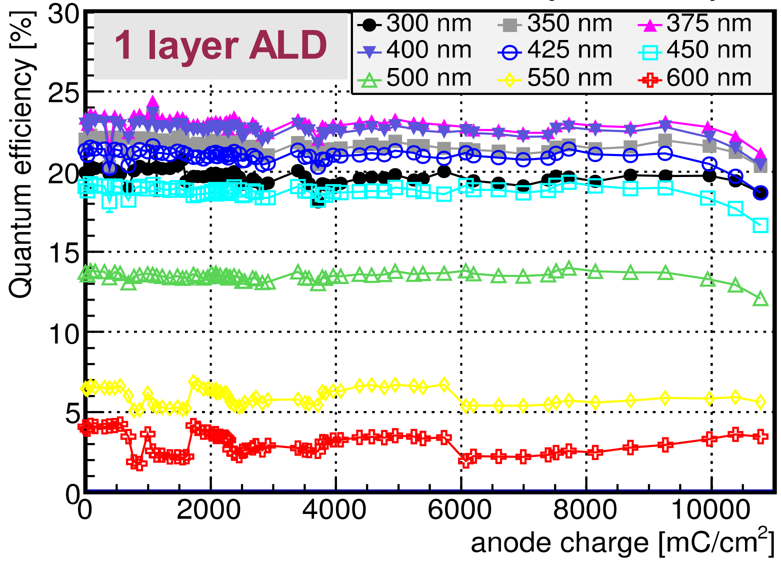


- BINP new PC: signature not easy to interpret
- Hamamatsu film and Photonis ALD: **once Q.E. starts degrading red light drops faster than blue** (→ work function changes)

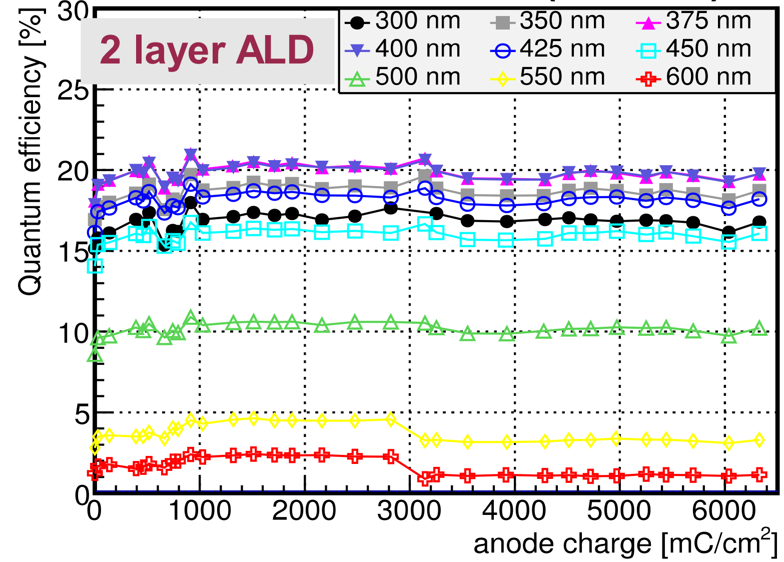
Q.E.(λ) vs. Anode Charge

PHOTONIS 2 inch

Photonis XP85112 (9001332)



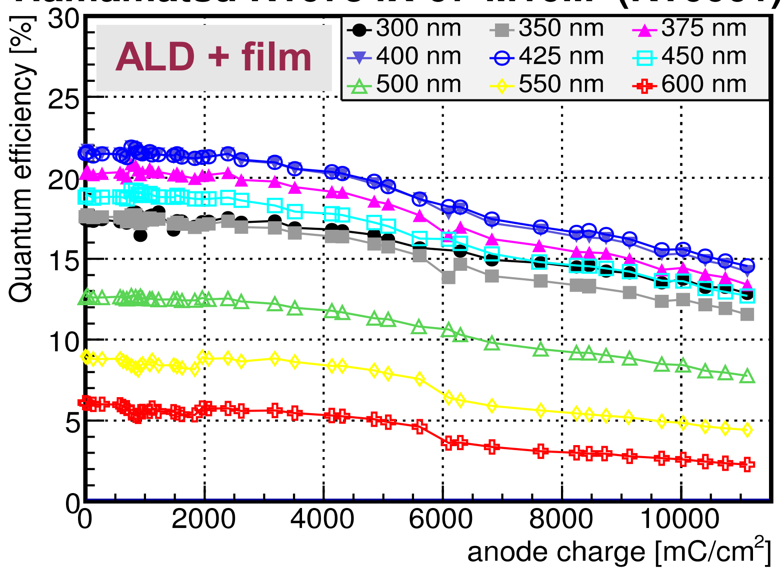
Photonis XP85112 (9001393)



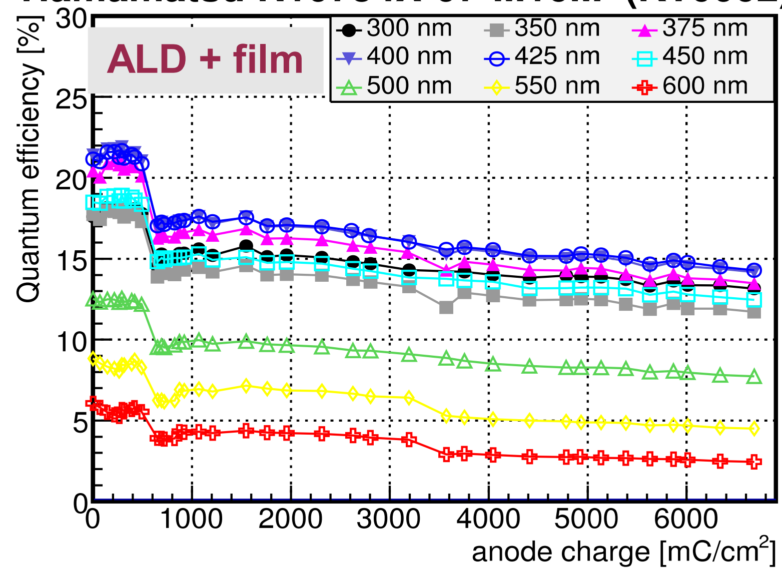
Status at
Feb. 1, 2016

Hamamatsu 1 inch

Hamamatsu R10754X-07-M16M (KT0001)

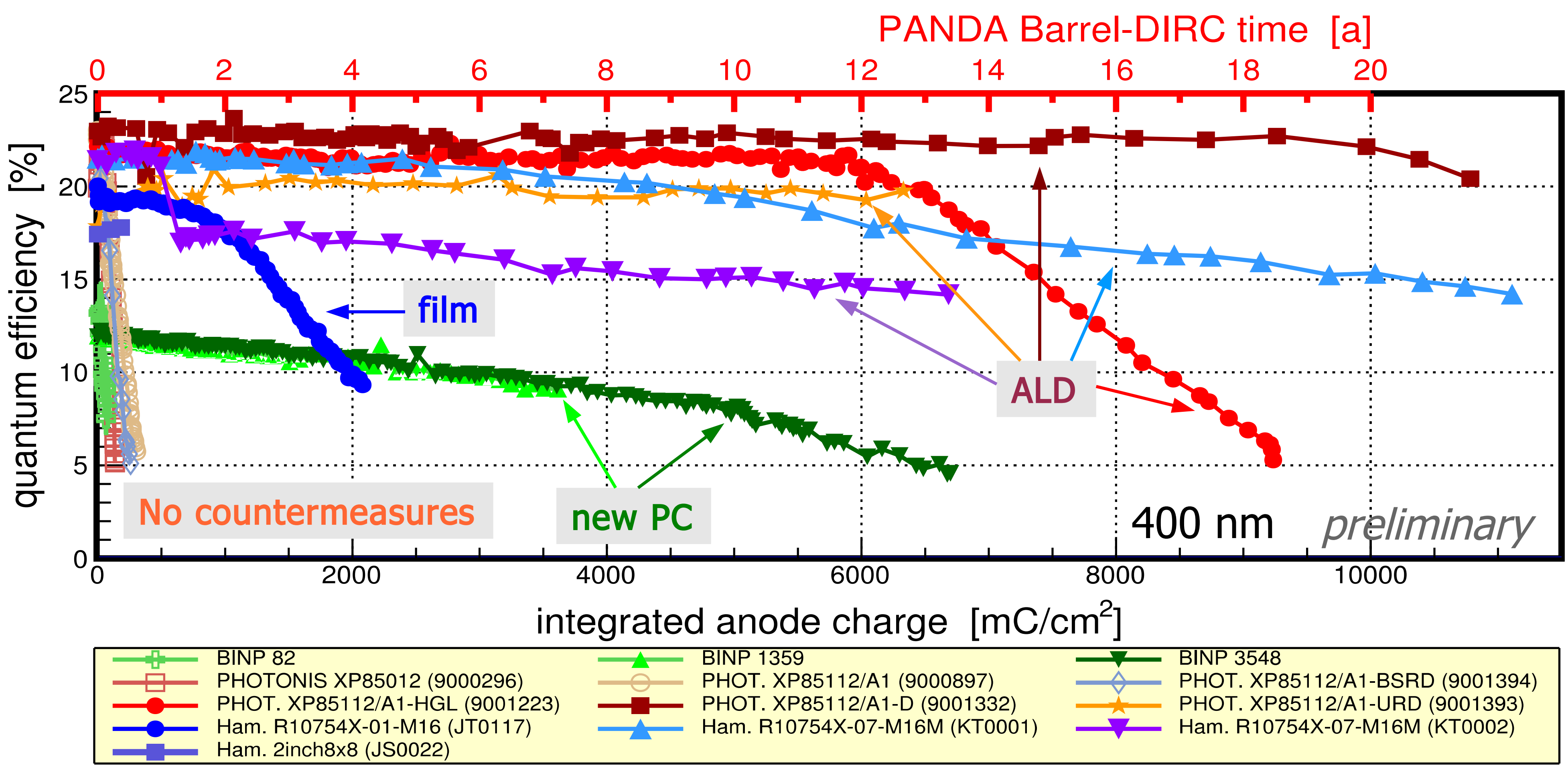


Hamamatsu R10754X-07-M16M (KT0002)



All ALD coated MCP-PMTs with >5 C/cm^2 integrated anode charge !

Lifetime of MCP-PMTs (Feb. 2016)



- Hamamatsu film MCP-PMT: Q.E. drops beyond 1 C/cm^2
- Photonis 9001332: no Q.E degrading observed up to 10 C/cm^2
- MCP-PMTs with ALD layers: **very good performance to >6 C/cm^2**

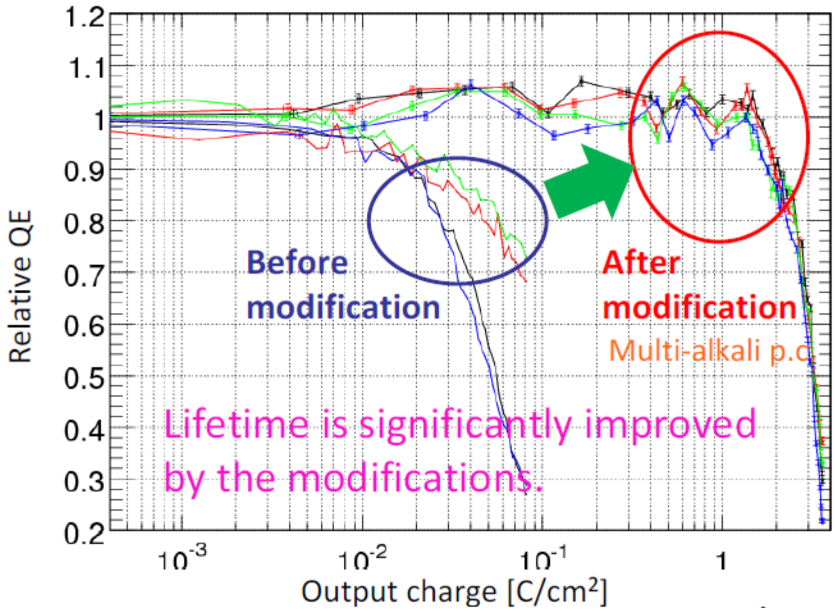
Illumination Overview

	Sensor ID	Integral charge (Feb. 1, 2016) [mC/cm^2]	QE start [%]	QE latest [%]	QE latest / QE start [%]	Comments
Photonis XP85112	9001223	**9234**	22.11	5.29	**24%**	Start: 23 Aug. 11 Stop: 22 Sep. 15
	9001332	**10783**	22.62	20.42	**90%**	Start: 12 Dec. 12 ongoing
	9001393	**6329**	19.05	19.77	**104%**	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)	**11110**	21.71	14.21	**65%**	Start: 20 Aug. 13 ongoing
	KT0002 (M16M)	**6683**	21.14	14.18	**67%**	Start: 21 Oct. 13 ongoing
	JS0022 (2x2 inch^2)	**189**	17.43	17.79	**102%**	Start: 11 Dec. 15 ongoing
BINP	1359	**3616**	12.27	9.06	**74%**	Start: 21 Oct. 11 Stop: 06 May 13
	3548	**6698**	12.23	4.58	**37%**	Start: 21 Oct. 11 Stop: 08 Jul. 15

Lifetime Results at Belle II

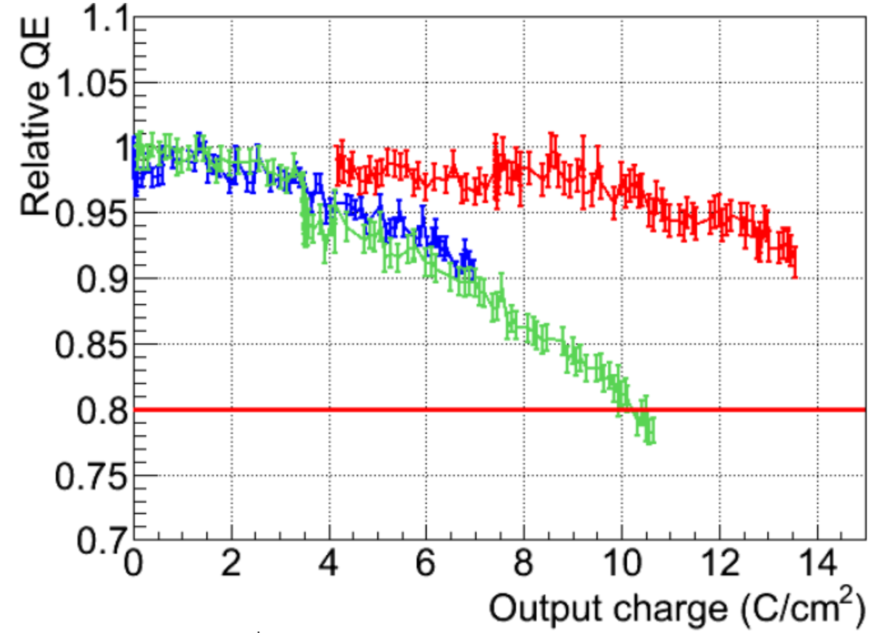
Hamamatsu MCP-PMT with film

NIM A629 (2011) 111

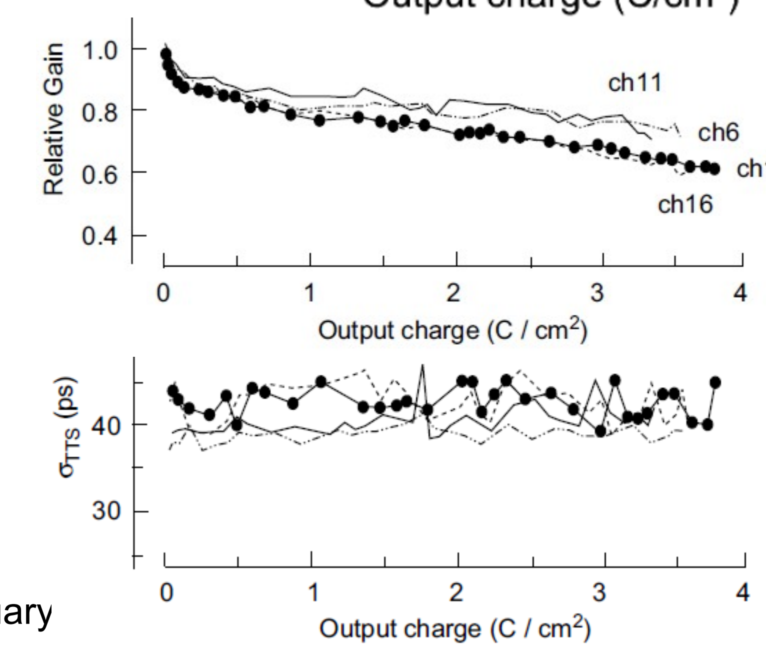


Hamamatsu MCP-PMT with ALD

K. Matsuoka, RICH2013



- Hamamatsu 1 inch MCP-PMTs with film good to ~2 C/cm^2
- Big improvement with ALD technique, but first results were not reproduced
- Moderate gain drop
- No changes in time resolution

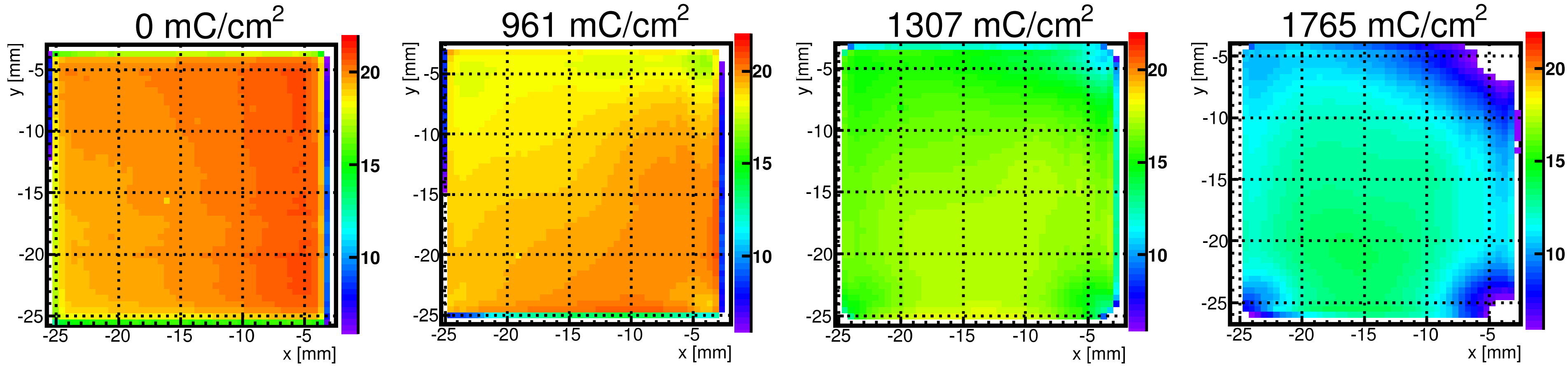


Q.E. Scans (Hamamatsu & BINP)

Q.E. measured at 372 nm

film **Hamamatsu R10754X-M16**

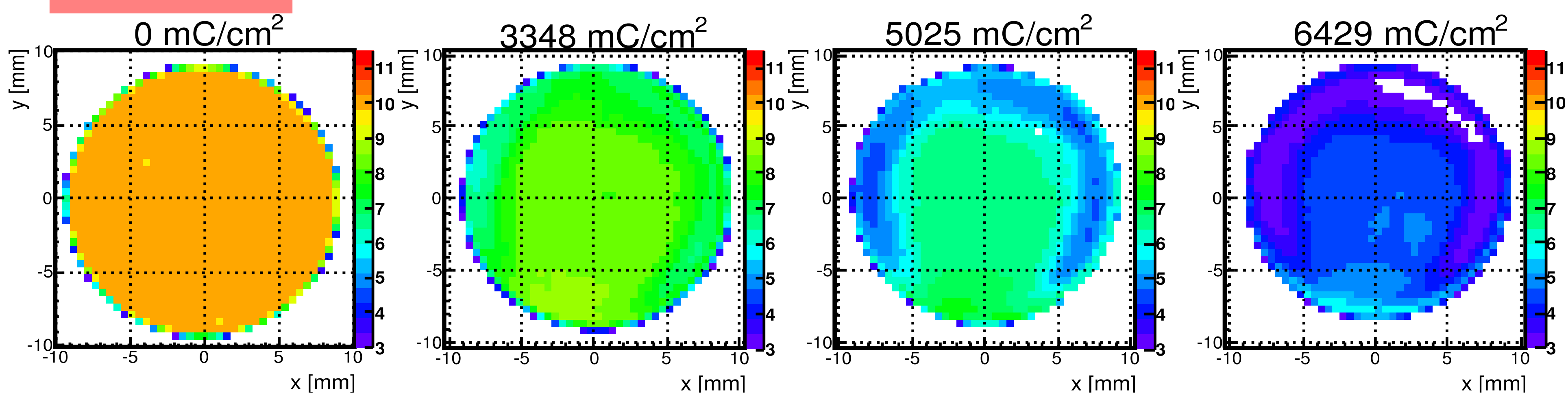
22 mm



new PC **BINP 3548**

QE degradation evolves from rims and corners

18 mm

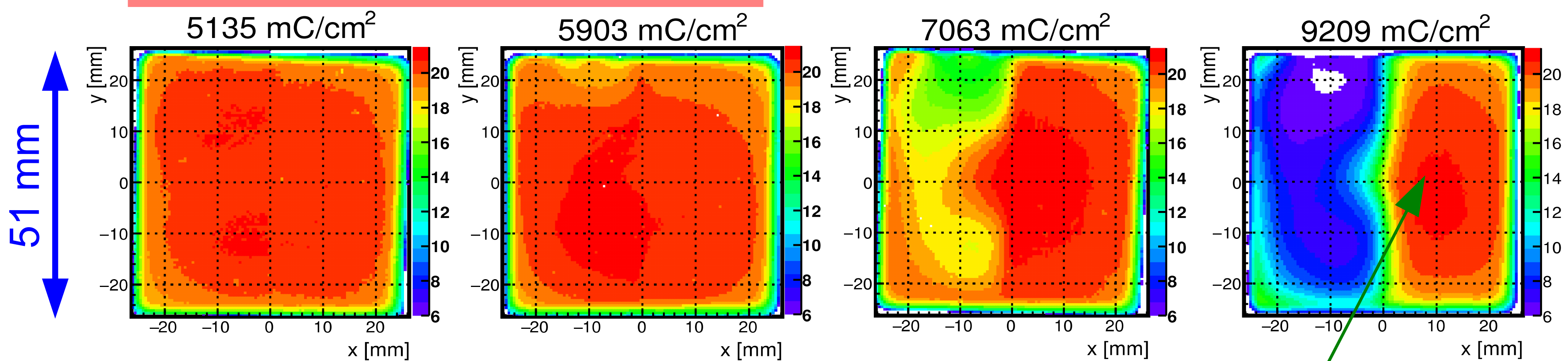


Q.E. Scans (PHOTONIS ALD)

Q.E. measured at 372 nm

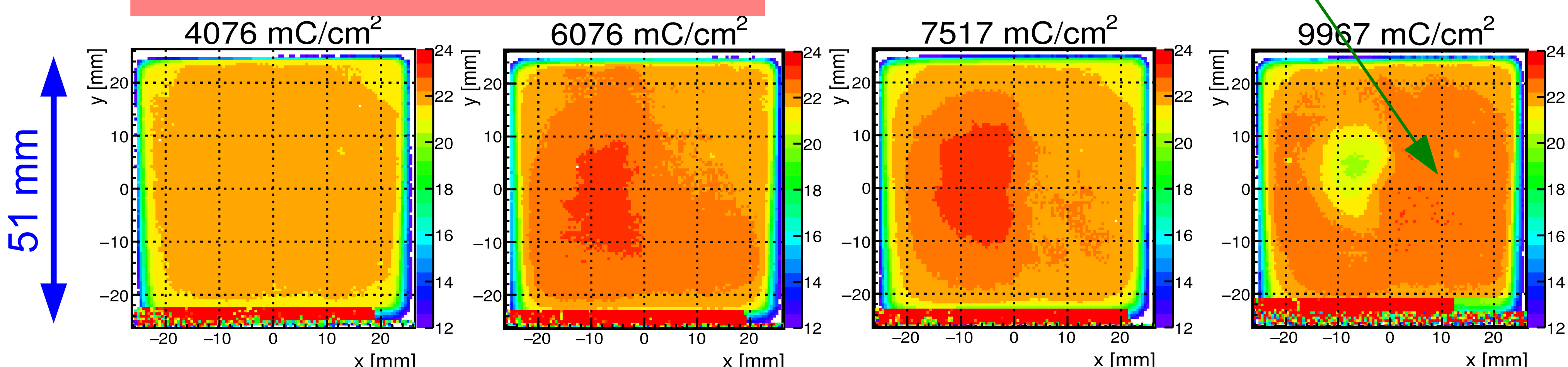
status December 2015

ALD **PHOTONIS XP85112 (9001223)**



right half of tube
not illuminated

ALD **PHOTONIS XP85112 (9001332)**



PC damage most likely caused by feedback ions !

Outlook

- Investigations to better understand the aging process
  - PHOTONIS XP85112 (9001223) is a unique MCP-PMT with an aged and an unaged half of the photo cathode (PC)
    - Is currently with PHOTONIS for non-destructive investigations of the PC
    - Spectroscopic ellipsometry to study refraction and absorption of both halves
    - I-V measurements of photoemission to check for work function changes
  - Identify the mass of the feedback ions with afterpulsing spectra
    - Many peaks and bumps visible in TOF spectra
    - Compare different types of MCP-PMTs (e.g., 10 µm, 25 µm, ALD, non-ALD)
- Accelerate aging and lifetime measurements
  - Saturation effects: aging speed depends on photon rate and intensity
    - M.Yu. Barnyakov and A.V. Mironov, 2011 JINST 6 C12026
  - Simultaneous current measurement at cathode and anode requires one potentialfree picoammeter

Summary

- Aging symptoms
  - PC work function changes (darkcount, wavelength dependence)
  - PC damage usually starts from rims and corners
  - Ion feedback dominant reason for aging
- **Tremendous lifetime increase of latest MCP-PMTs** due to recent design improvements
  - **application of ALD technique (x50 lifetime improvement)**
  - **huge step forward !**
- Equipping the PANDA DIRCs and other high rate detectors with MCP-PMTs appears feasible