Recent Developments with Microchannel-Plate PMTs

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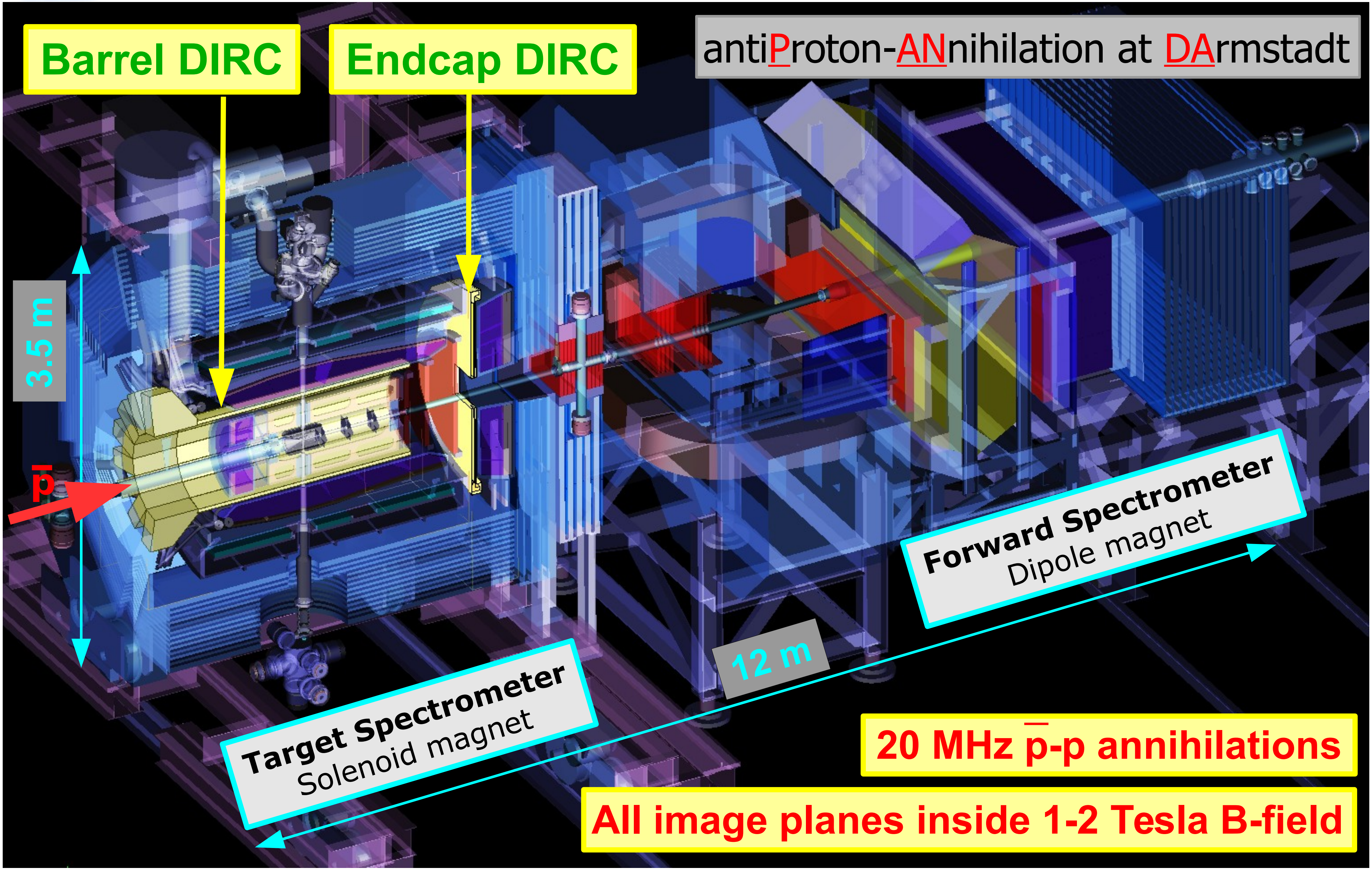
- Introduction and motivation
- Properties of new 2" Hamamatsu MCP-PMT
- Status of aging test results
- Trying to understand PC aging mechanism
- Outlook and summary

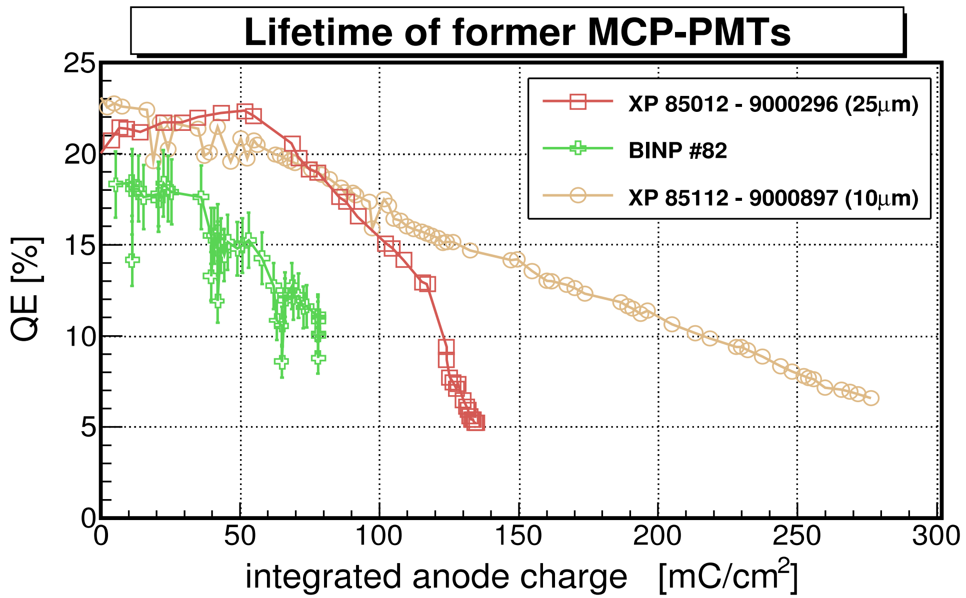
$\overline{\text{P}}$ANDA Detector at FAIR



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 Tesla
  - Excellent time resolution <50 ps
  - Low dark count rates
- Barrel DIRC
  - Pixel size: ~ 6 x 6 mm^2
  - Photon rate: ~200 kHz/cm^2
  - **10 years anode charge: 5 C/cm^2**
- Endcap DIRC
  - **Pixel size: ~ 0.5 x 16 mm^2**
  - Photon rate: up to 1 MHz/cm^2
  - **10 years anode charge: >5 C/cm^2**

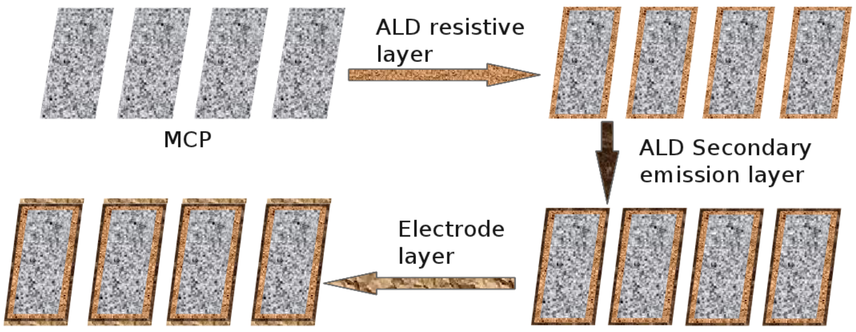
Status in 2011



Attempts to Reduce Aging

- Improved vacuum quality
- Cleaning of MCP surfaces by electron scrubbing techniques
- Thin (5-10 nm) Al_2O_3 films before or between MCPs [NIM A629 (2011) 111]
- Modified and more robust photo cathodes [JINST 6 C12026 (2011)]
- Deposition of ultra-thin atomic layer (MgO, Al_2O_3) on MCP substrate
  - Arradiance Inc. → PHOTONIS, LAPPD, ...
  - 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

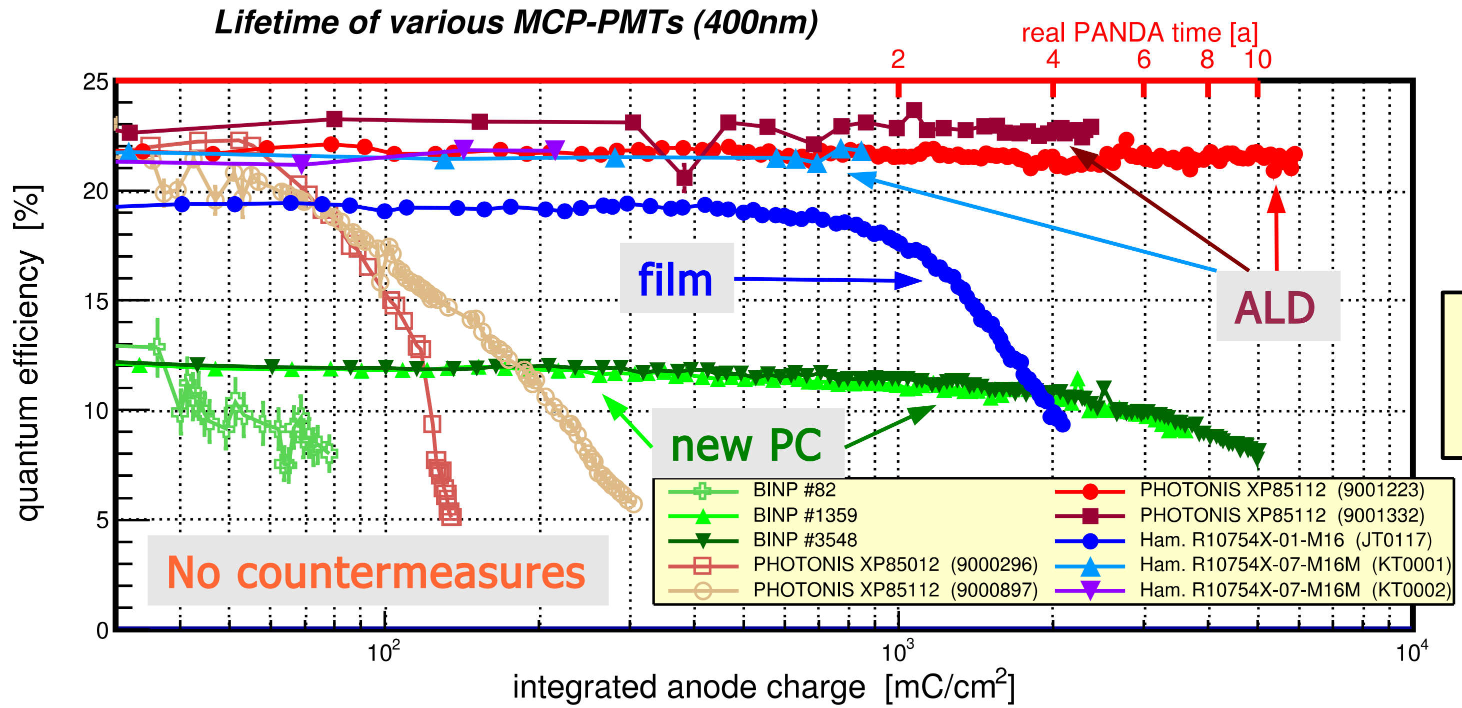
[NIM A639 (2011) 148]



!! 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:

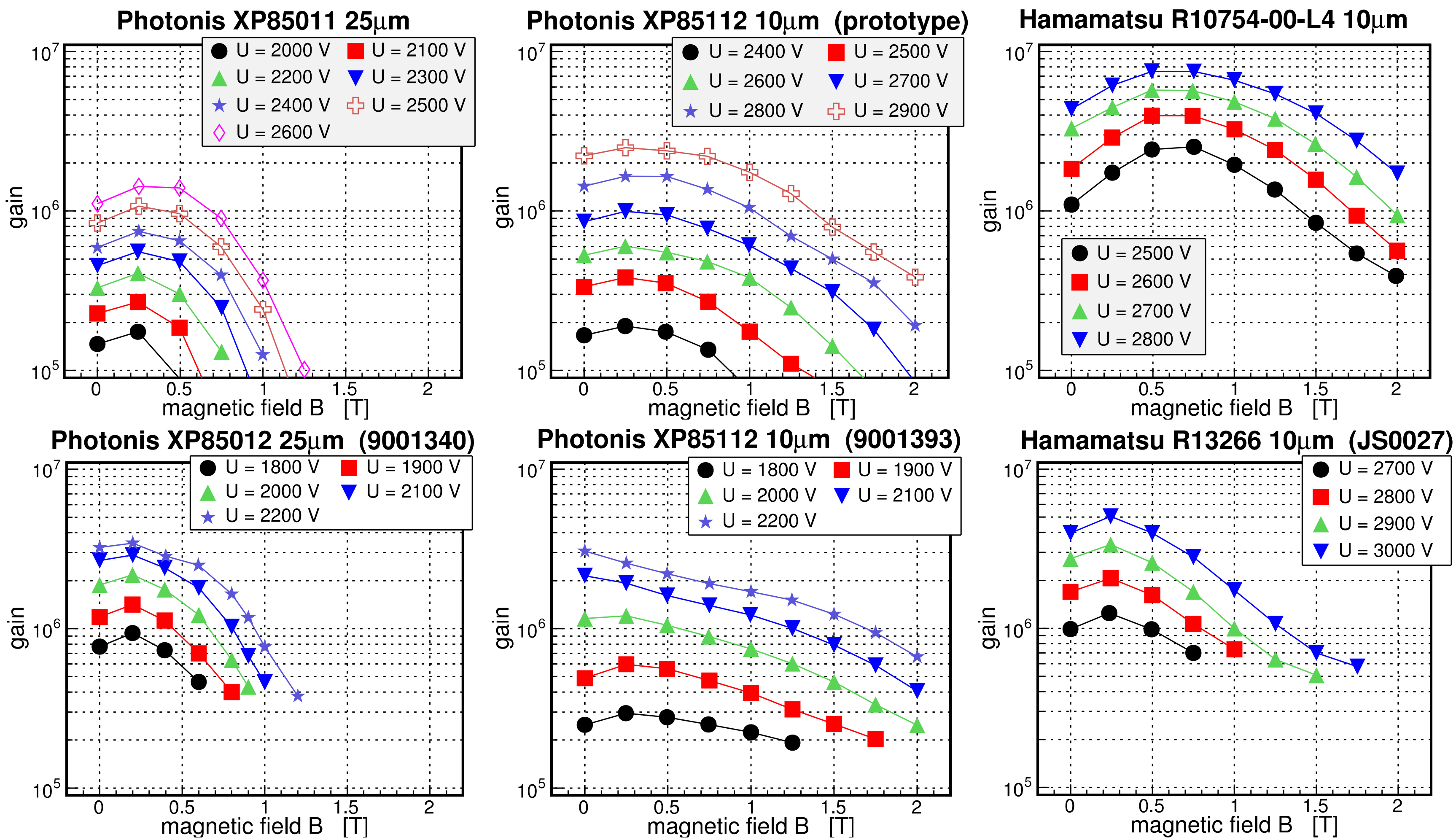


ALD technique is superior

Gain of ALD Tubes

Non-ALD

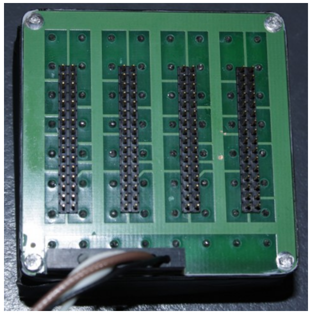
ALD

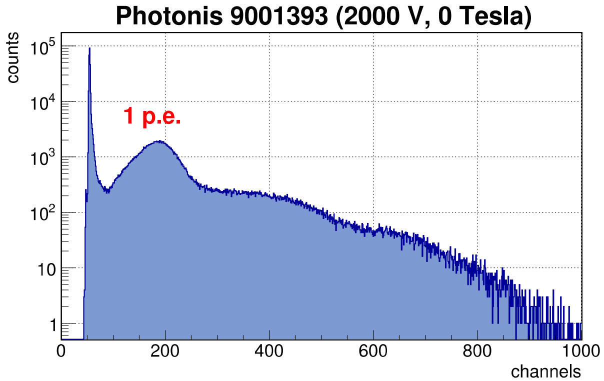


- Tendency of faster gain drop inside magnetic fields in ALD tubes
- Reason could be higher SEE coefficients → earlier saturation

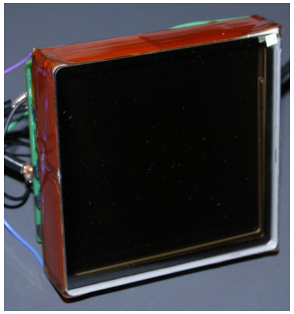
2 inch Multi-Anode MCP-PMTs

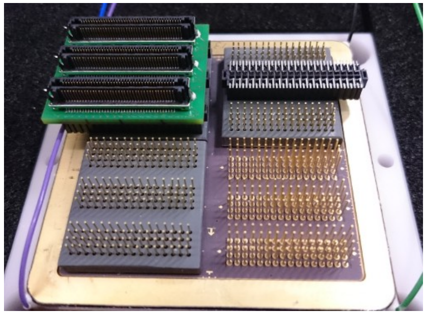
- **Photonis**
  - Layout existent since Burle Planacon
  - ALD surfaces; no film
  - active area ratio: 81%
  - Available as 8x8 (Barrel DIRC) and 3x100 (Endcap DIRC) pixel versions

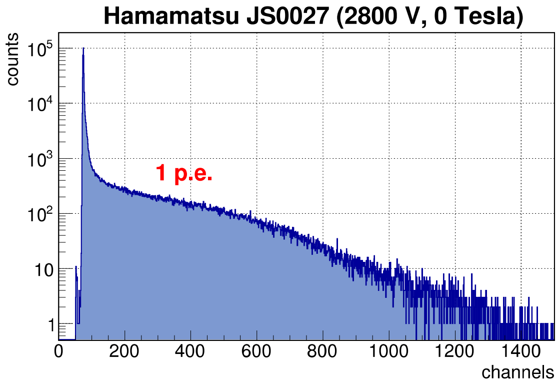




- **Hamamatsu**
  - First prototypes developed in 2014
  - ALD surfaces + film in front of 1st MCP
  - Slightly less active area ratio: 70%
  - Available as 8x8 (Barrel DIRC) and 6x128 (Endcap DIRC) pixel versions





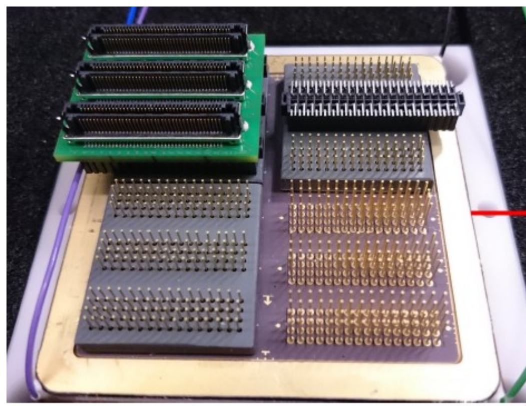


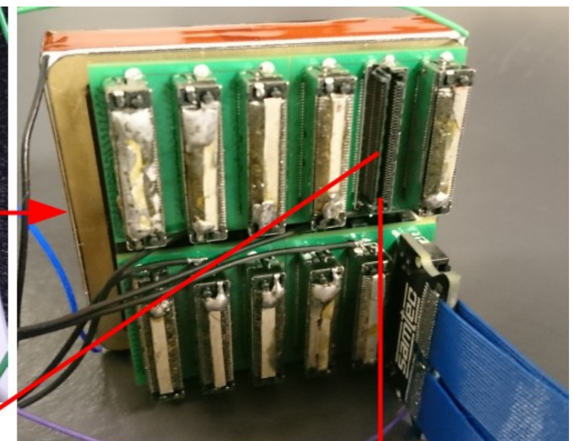
Readout of 128x6 Hamamatsu MCP

MCP backplane with 12 blocks of 64 pins each:
rather difficult readout for characterization (not yet ASICs)

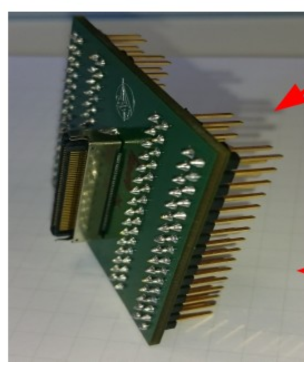
MCP backplane with one readout board:

- Covers 3 64-pin blocks
- Lower side: three 0.05" Samtec plugs with 4x20 pins (FOLC-120-02-L-Q)
- Upper side: three 0.05" Samtec plugs with 2x40 pins (LSHM-140-02.5-L-DV-A-S-TR)





MCP backplane with four readout boards connected



Adapter board for 64 pins from 0.05" to 0.10" pitch

80-channel coax-cable connects to 1 adapter board

Possibility to read out single blocks directly or up to all 768 channels simultaneously with coax-cables

Properties of 2" Hamamatsu (8x8)

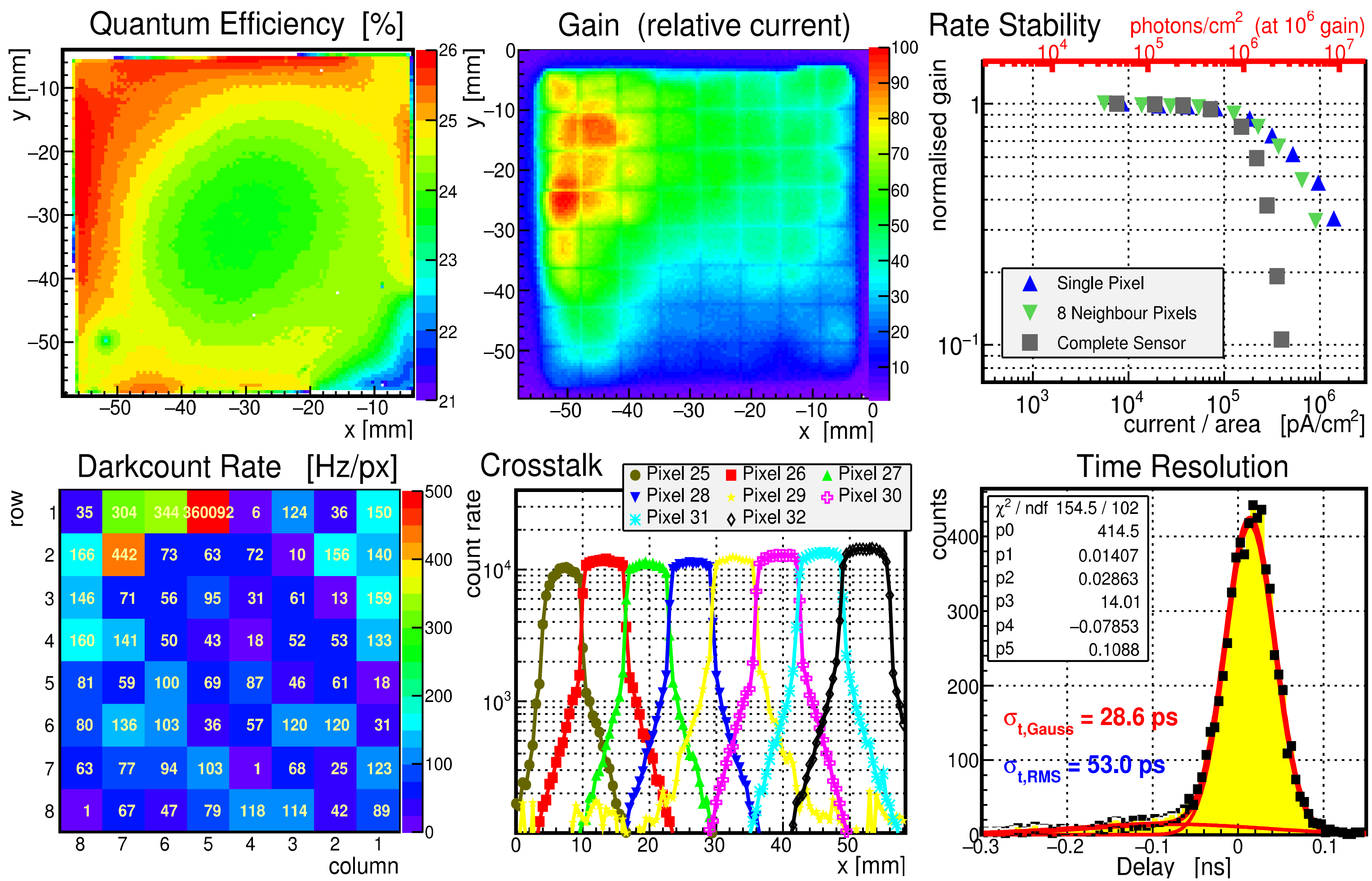
JS0035

still negative

- QE homogeneity improvable
- Gain very non-homogeneous
- Rather low rate capability

positive

- Very low dark count rate
- Good cross talk behavior
- Excellent time resolution

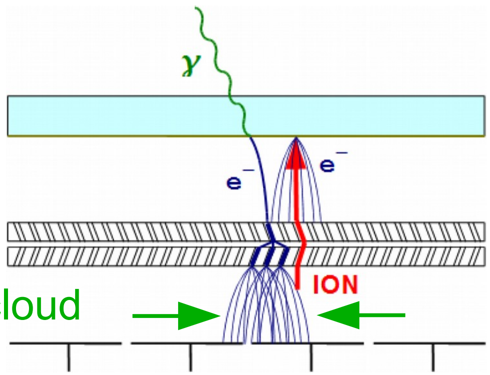


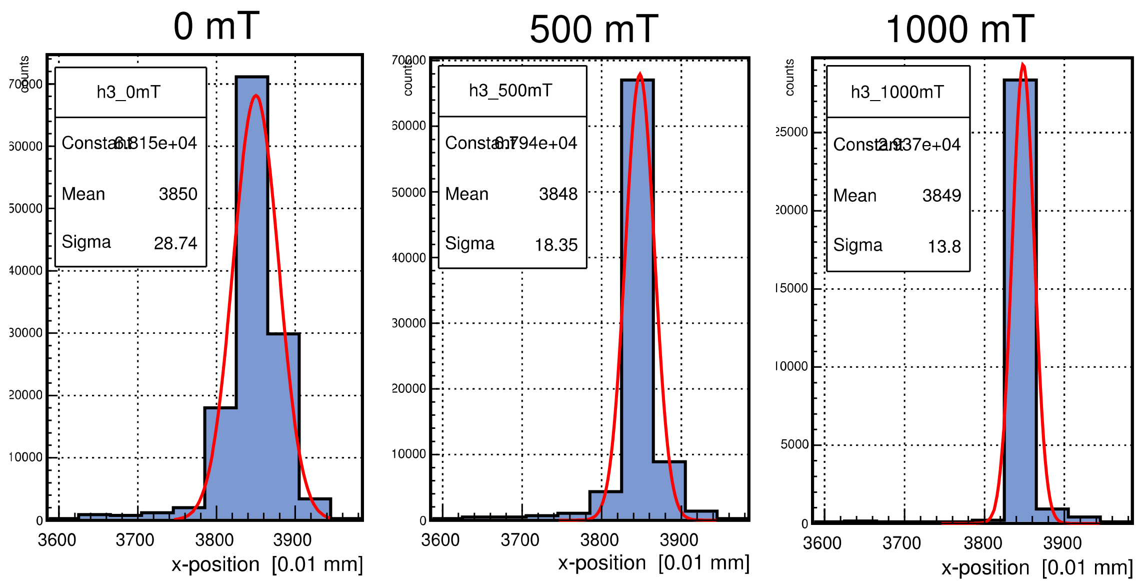
New 2" Hamamatsu MCP-PMT (R13266) prototype shows promising features with room for improvement

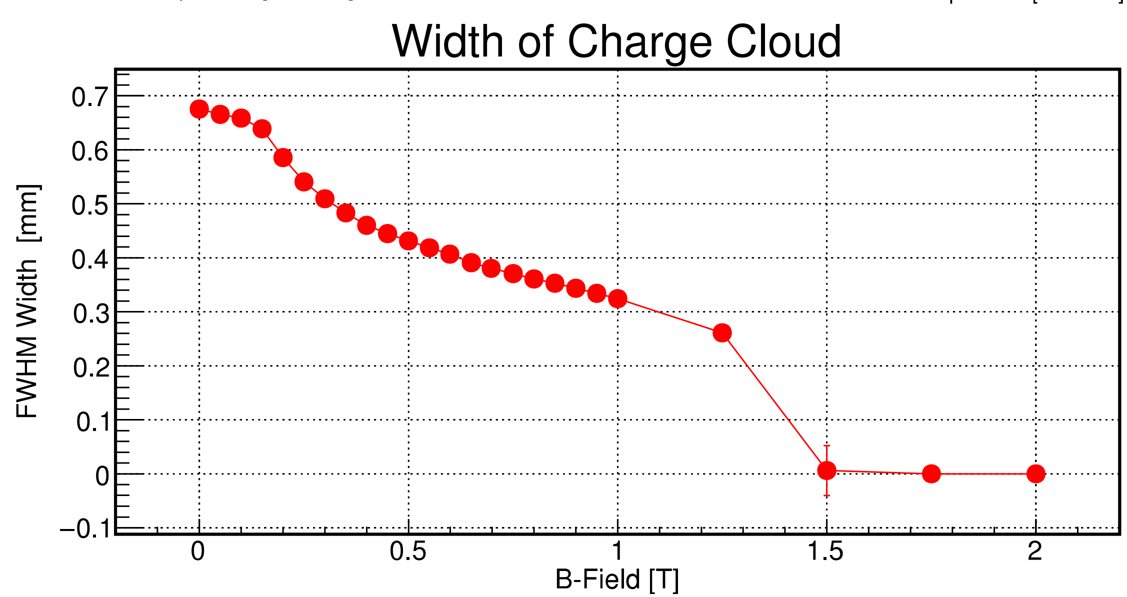
Measure Width of Charge Cloud

T. Gys, NDIP 2014

width of charge cloud



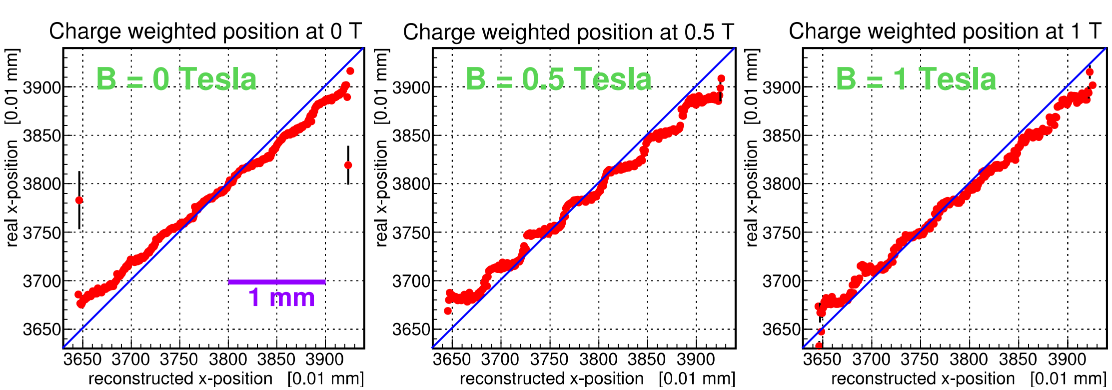


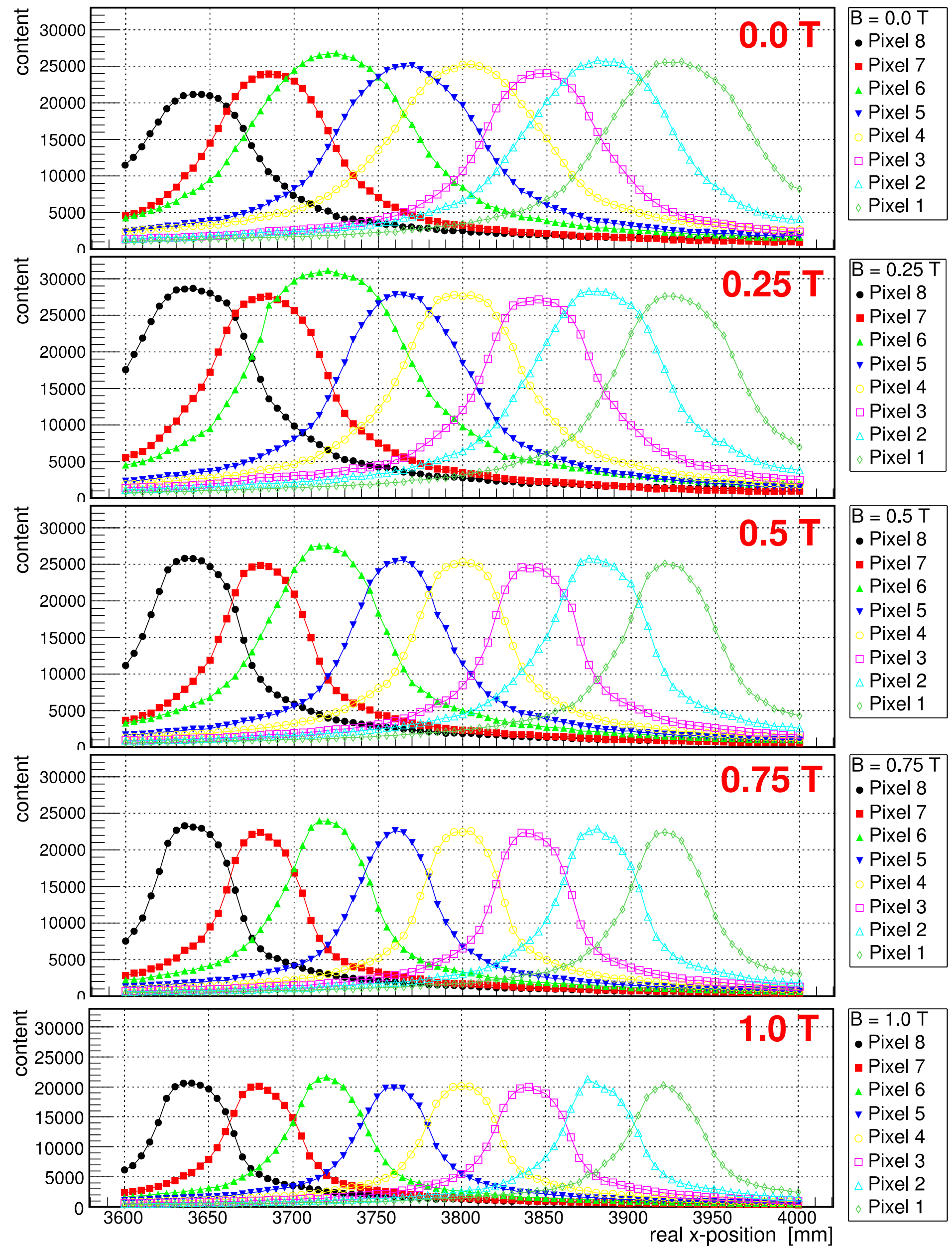


- Hamamatsu 6x128 pixels inside magnetic field
  - Illuminate 1 pixel with <50 μm focus
  - Read out 8 adjacent pixels (0.4 mm pitch)
  - Measure counts above a certain threshold (10 chan. ~ 0.04 p.e.)
  - Plot distribution as a function of the magnetic field
  - Width of distribution shrinks with increasing B-field
- **0.3 mm FWHM resolution at 1 T**

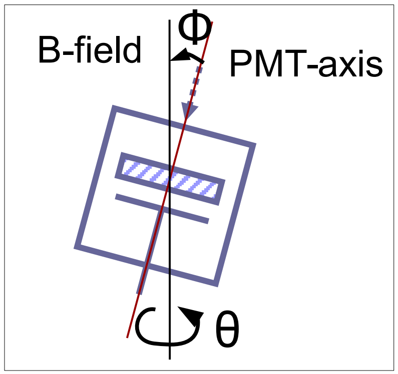
Crosstalk and Position Resolution

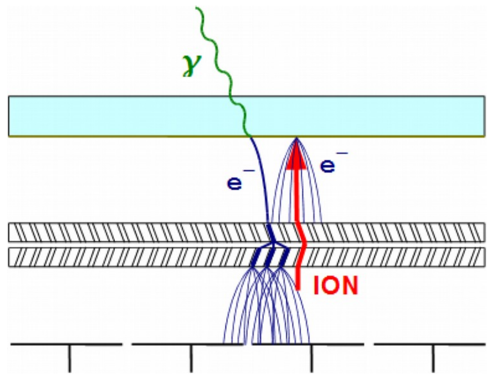
- Hamamatsu MCP-PMT with 6x128 pixels inside magnetic field
  - Diameter of laser spot <50 μm
  - Read out 8 adjacent pixels (0.4 mm pitch)
  - Plot counts in each pixel at given laser position (thresh = 0.04 p.e.; 50 μm steps)
- Position resolution
  - Rather long tails → **electronic crosstalk?**
  - Photonis MCP-PMTs looks better → Talk M. Düren
  - Peak width gets smaller at higher B-field
- Good linearity with charge weighting
  - Off at sides because of limited number of anodes



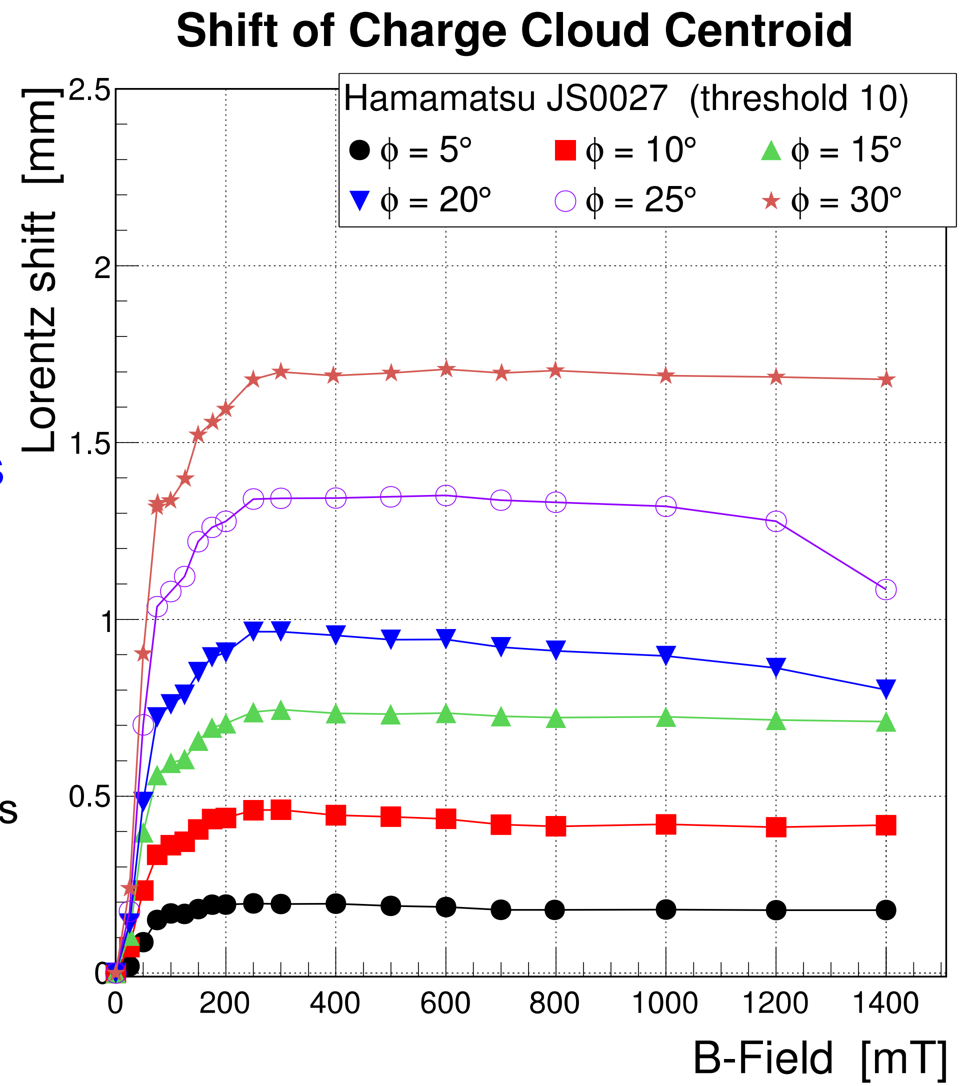


Measure Lorentz Shift in MCP-PMT





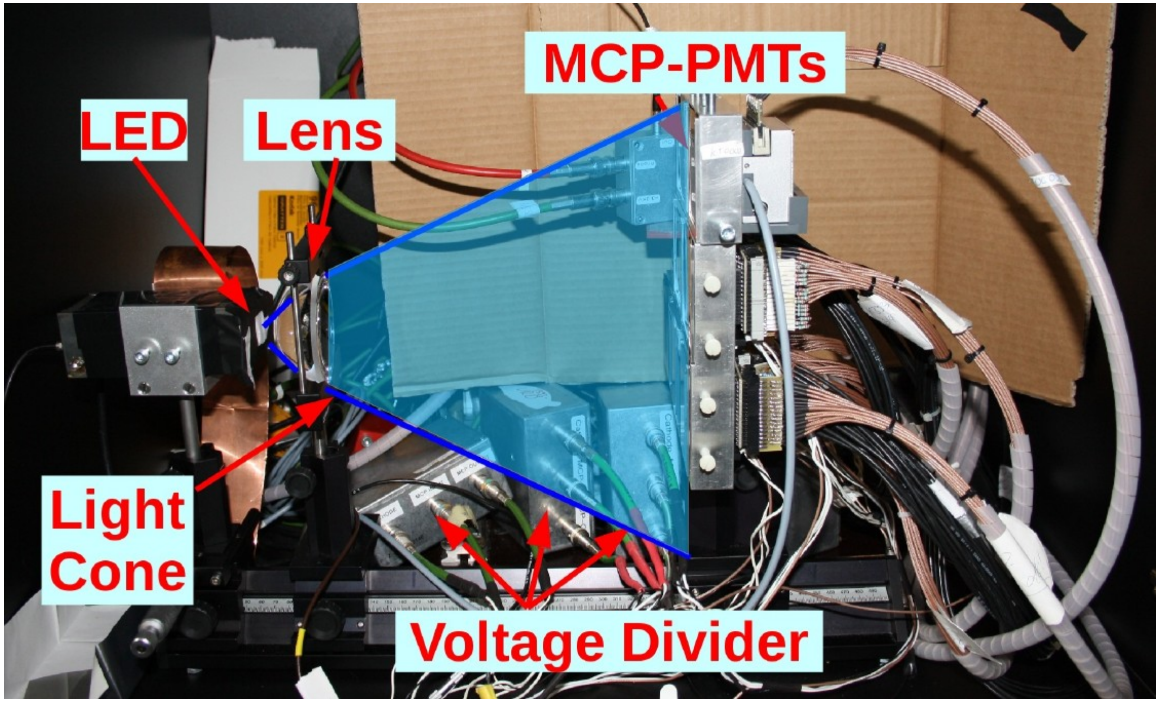
shift of charge cloud



- Hamamatsu MCP-PMT with 6x128 pixels inside magnetic field
  - Diameter of laser spot <50 μm
  - Always point laser to same pixel (at Φ = 0°)
  - Read out 8 adjacent pixels (0.4 mm pitch)
  - Calculate charge weighted position along tilt axis
  - → **measures Lorentz shift inside B-field**
- Position shift
  - Saturation reached at ~0.25 Tesla
  - Maximum shift of 1.7 mm (~4 pixels) at Φ = 30°

Measurement of MCP Lifetime

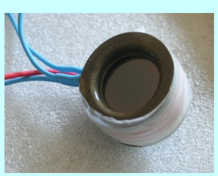
- Continuous illumination
  - 460 nm LED at 0.25 to 1 MHz rate attenuated to single photon level
    → 3 to 20 mC/cm^2/day



- Permanent monitoring
  - MCP pulse heights and LED light intensity
- Q.E. measurements
  - 250–700 nm wavelength band with monochromator $\Delta\lambda$ = 1 nm
  - Every 2-3 weeks (first days): wavelength scan
  - Every 3-4 months (first weeks): complete surface scan at 372 nm

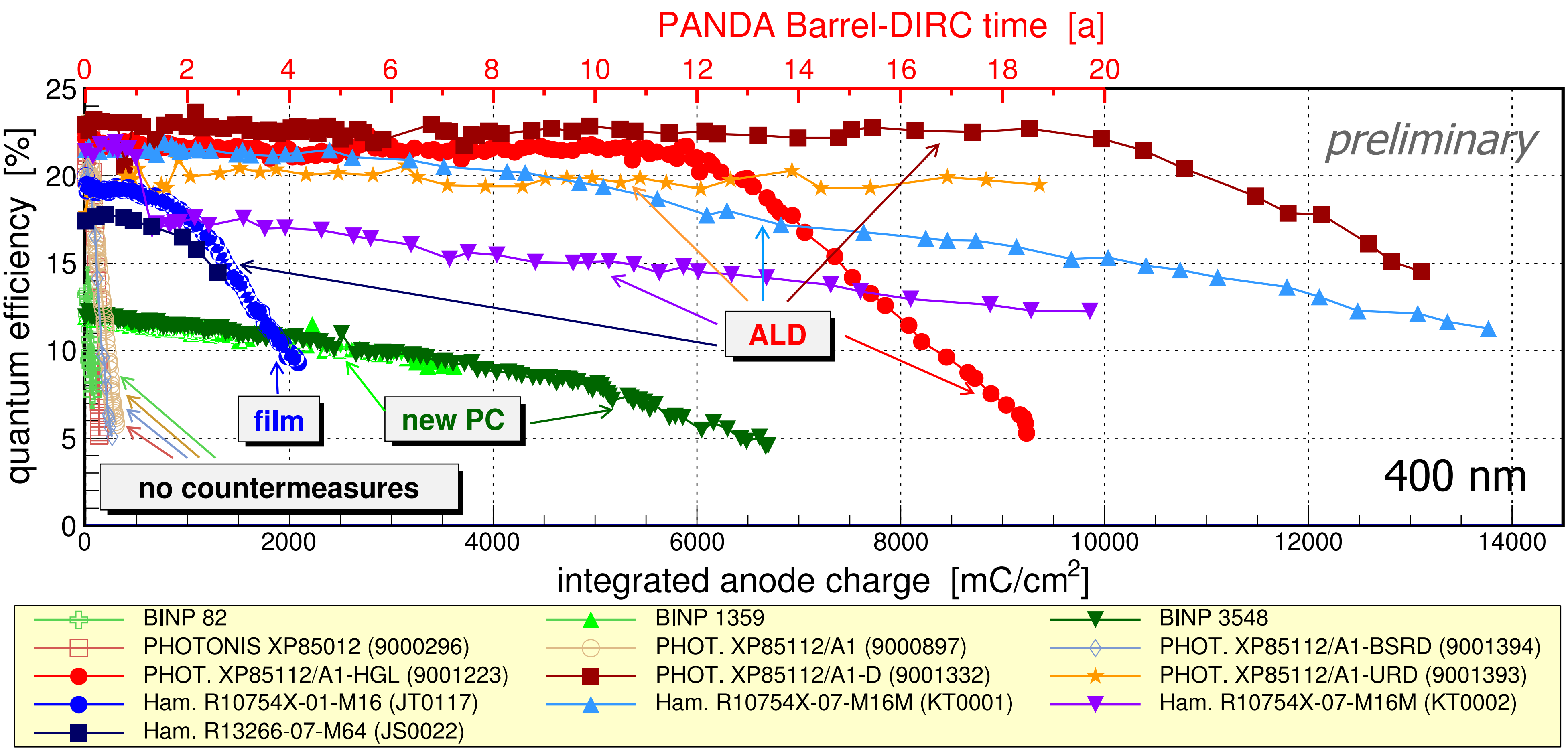
Lifetime-Investigated MCP-PMTs

	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)	9² π	53x53	53x53	53x53	22x22	22x22	51x51
total area (mm²)	15.5² π	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 ~5 years ago
- Hamamatsu 1 inch ALD tubes measurement started ~3 year ago
- Hamamatsu 2 inch ALD tube started in Dec. 2015

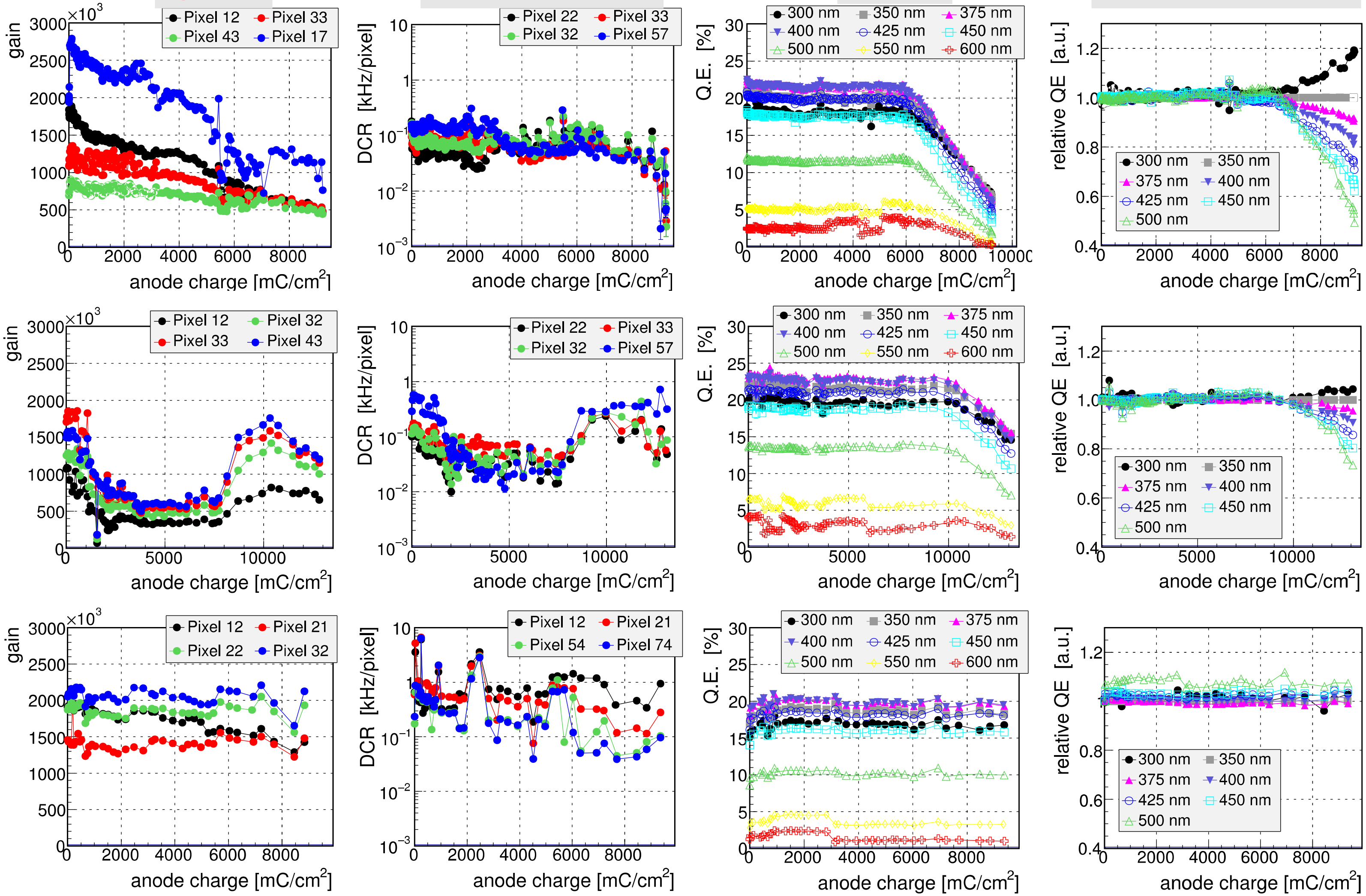
Lifetime of MCP-PMTs (Aug. 2016)



- Hamamatsu film MCP-PMT: Q.E. drops beyond 1 C/cm^2
- Photonis 9001393: no Q.E degrading observed up to ~10 C/cm^2
- MCP-PMTs with ALD layers: **very good performance to >6 C/cm^2**

Gain, DCR and QE (Photonis)

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



XP85112 (9001223)
1 ALD layer

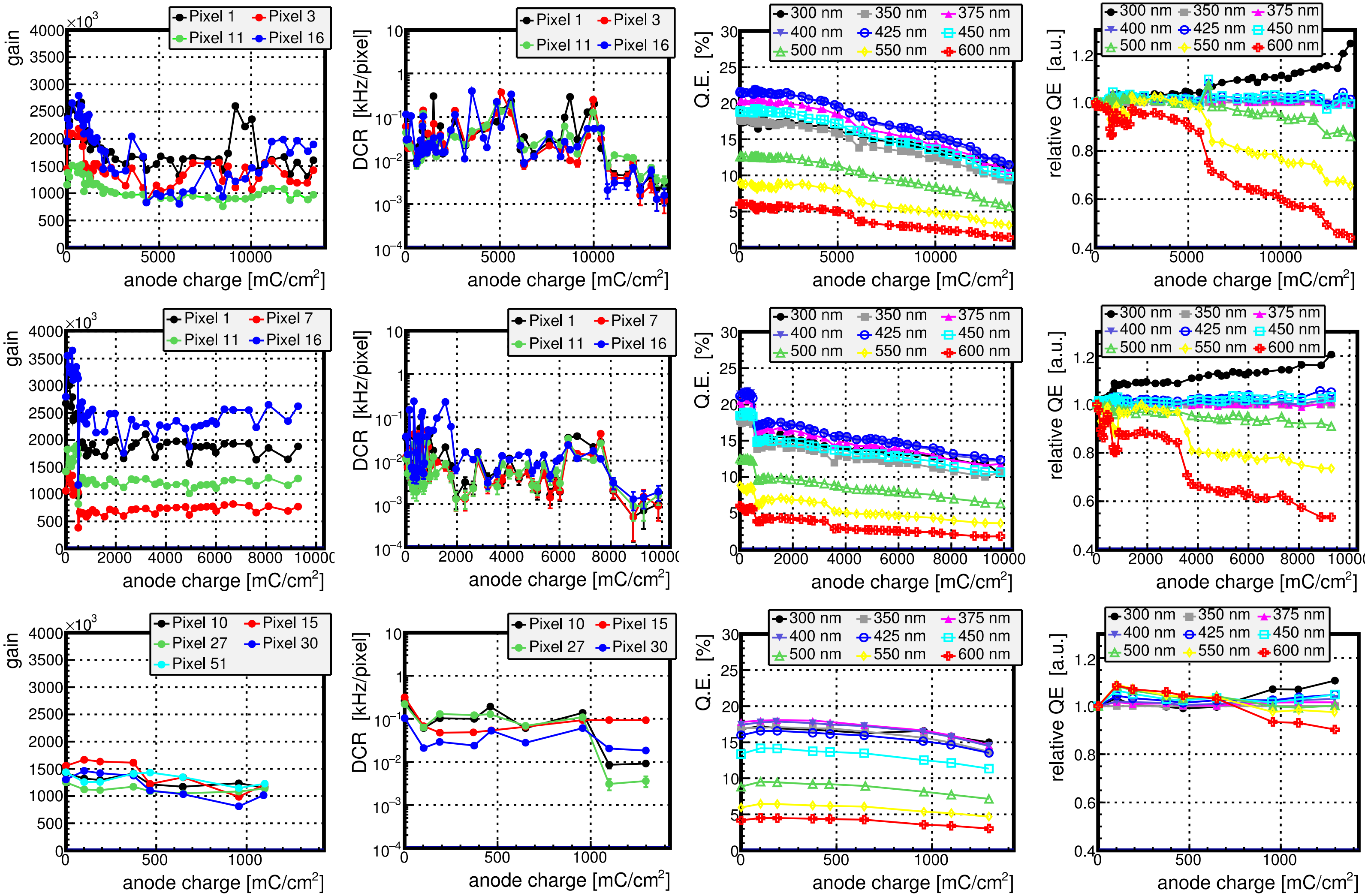
XP85112 (9001332)
1 ALD layer

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 ~10 C/cm^2

Gain, DCR and QE (Hamamatsu)

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



R10754X-07-M16M (KT0001)

1 ALD layer
+ film between MCPs

R10754X-07-M16M (KT0001)

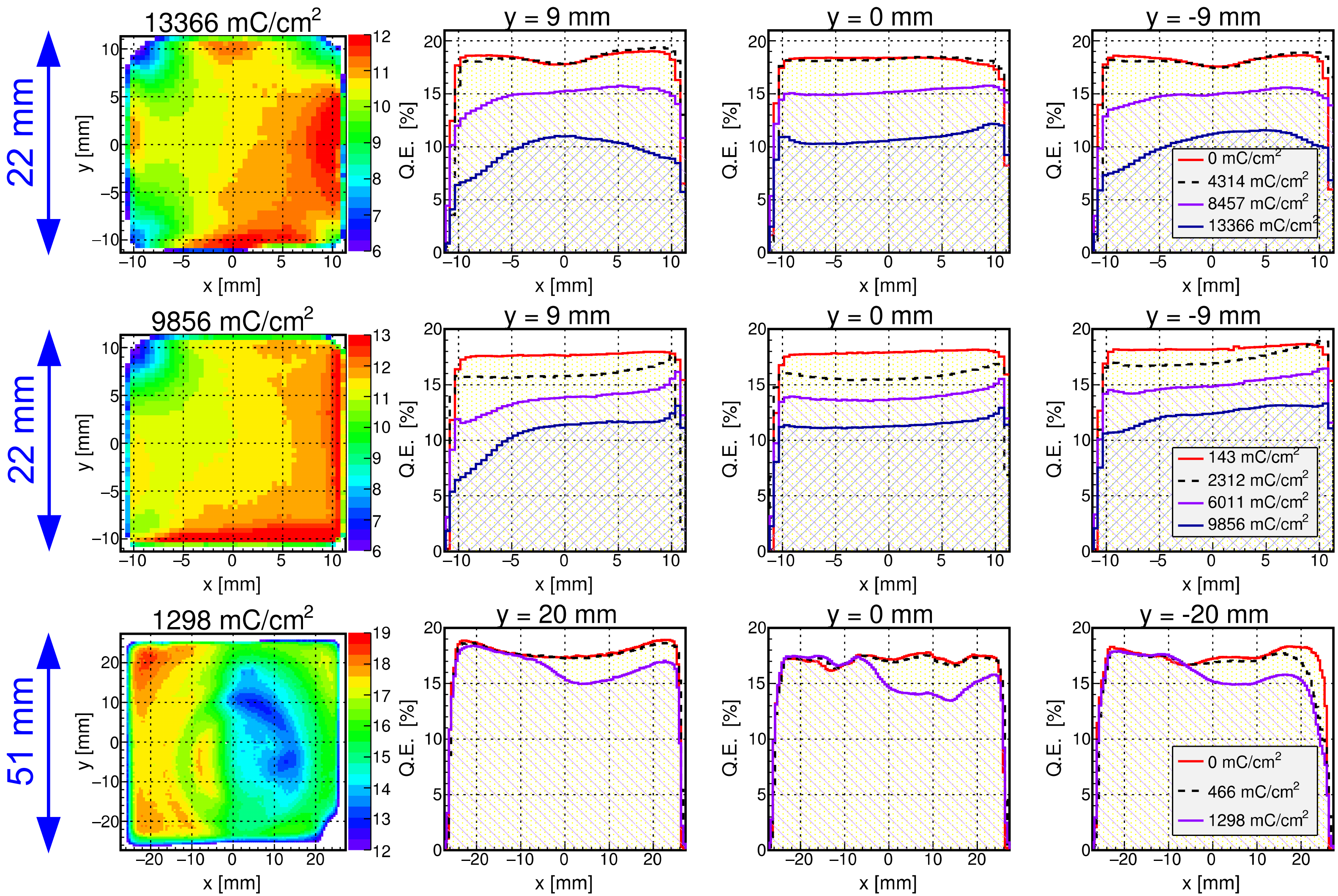
1 ALD layer
+ film between MCPs

R13266-07-M64 (JS0022)

1 ALD layer + film
in front of 1st MCP

- gain moderately stable and DCR decreases slightly
- Moderate but continuous QE degradation with wavelength dependence

Q.E. Scans (Hamamatsu ALD)



Q.E. at 372 nm

R10754X-07-M16M (KT0001)

1 ALD layer
+ film between MCPs

R10754X-07-M16M (KT0002)

1 ALD layer
+ film between MCPs

R13266-07-M64 (JS0022)

1 ALD layer + film
in front of 1st MCP

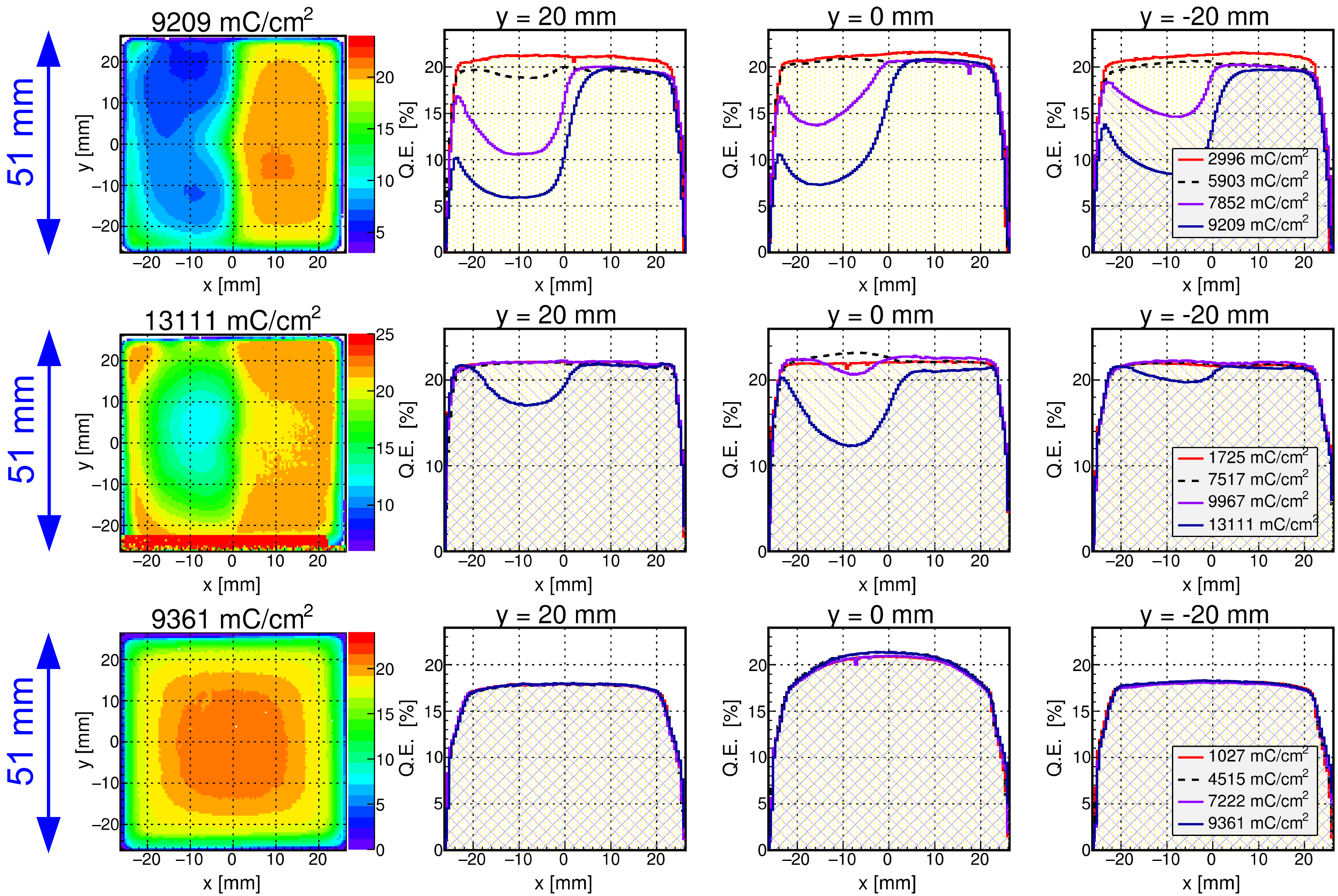
left half of tube
not illuminated

1": steady QE degradation up to 10 C/cm^2; corners more serious

2": significant QE degradation starts already after ~1.3 C/cm^2

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

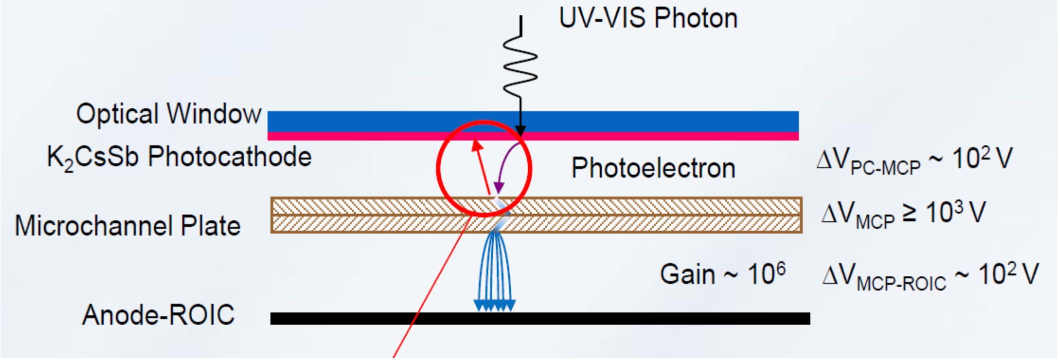
1 ALD layer: QE degradation starts at 6 C/cm^2 and 10 C/cm^2

2 ALD layers: no sign of QE degradation up to ~9.4 C/cm^2

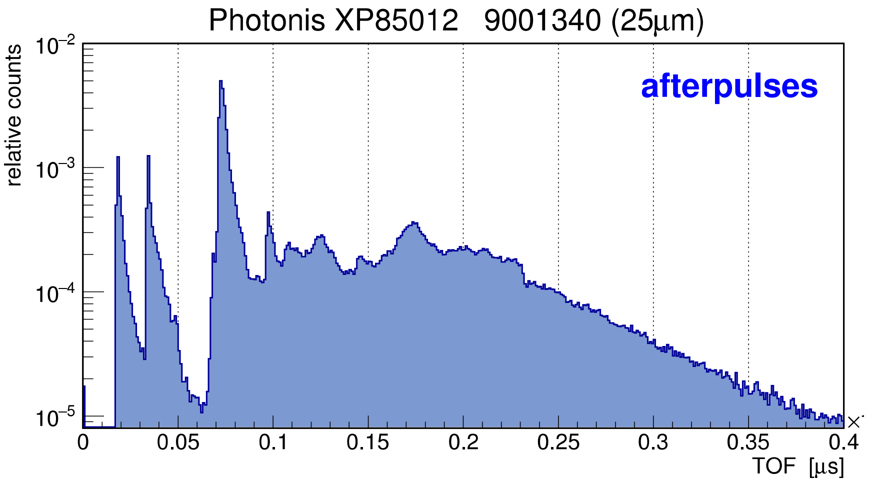
Possible Causes of MCP Aging

- 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, 2016]



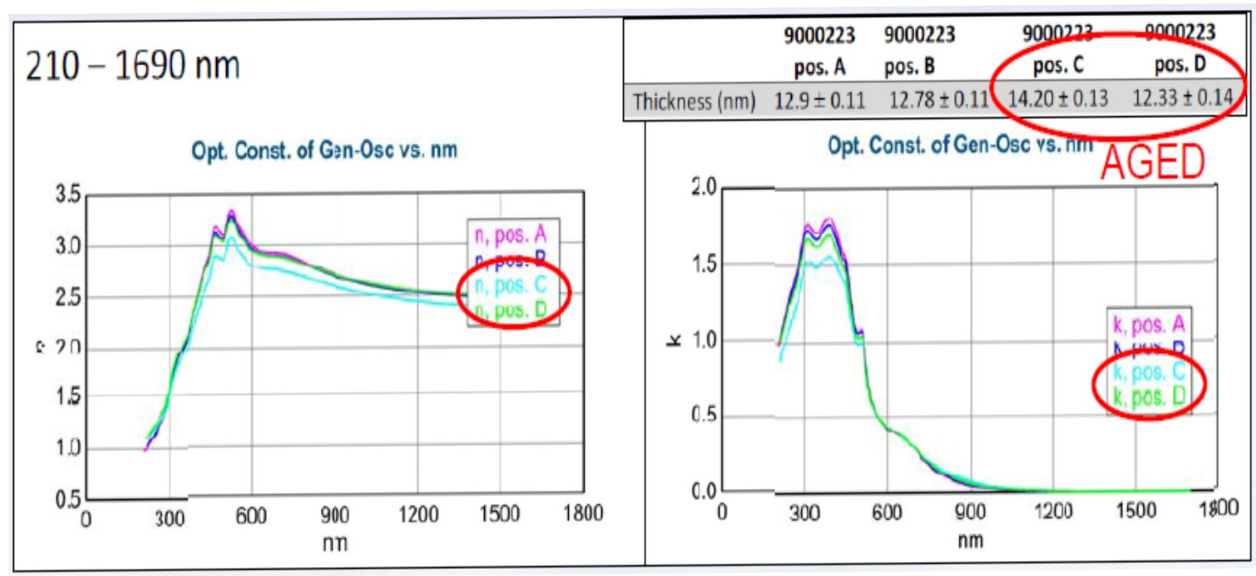
  – Ions accelerated towards photo cathode (**ion feedback**)
    - Ions hit and may react with PC
    - Order-of-magnitude ~keV ions
    - Light ions (H^+, H_nO^+) confirmed by TOF
    - Heavier ions more difficult to identify (expected K, Cs, Pb, Si)

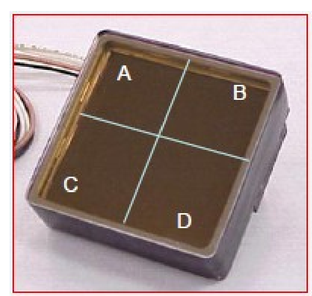


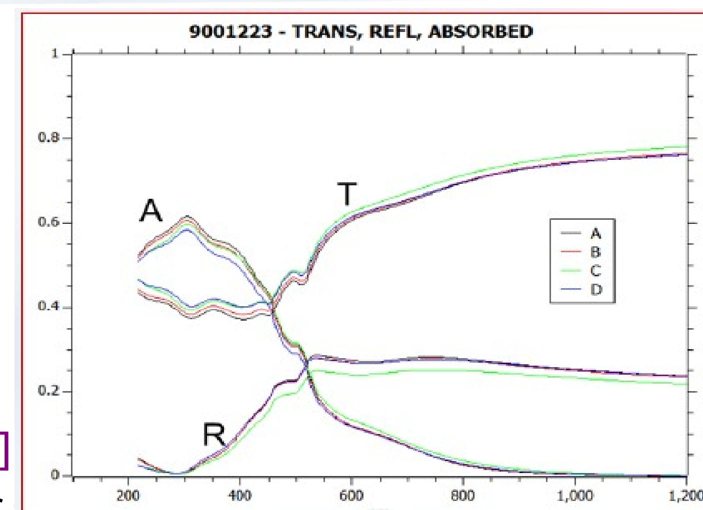
  – PC gets damaged → QE loss
    - **Mechanism unknown !**

Aging Mechanism (Absorption?)

- According to 3-step photo-emission model “damage” may occur on any of the processes related to absorption, diffusion and escape at the surface barrier
- Accessible measurements
  - Quantum efficiency (QE)
  - p.e. energy distribution with RPA (retarding potential analyzer)
  - Optical absorption
- Optical measurements
  - Backside (through-substrate) spectroscopic ellipsometry measurements
  - Results of 4 quadrants indistinguishable (2 covered, 2 aged)
  - **Bulk structure unchanged**
    → normal e-h pair generation
    → no change in photon absorption
  - Big changes in optical absorption could be seen by eye!





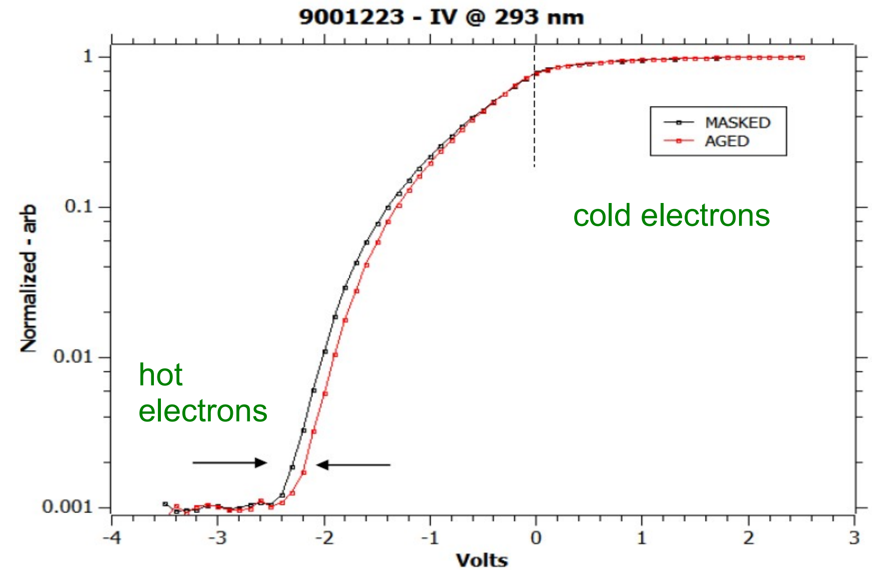


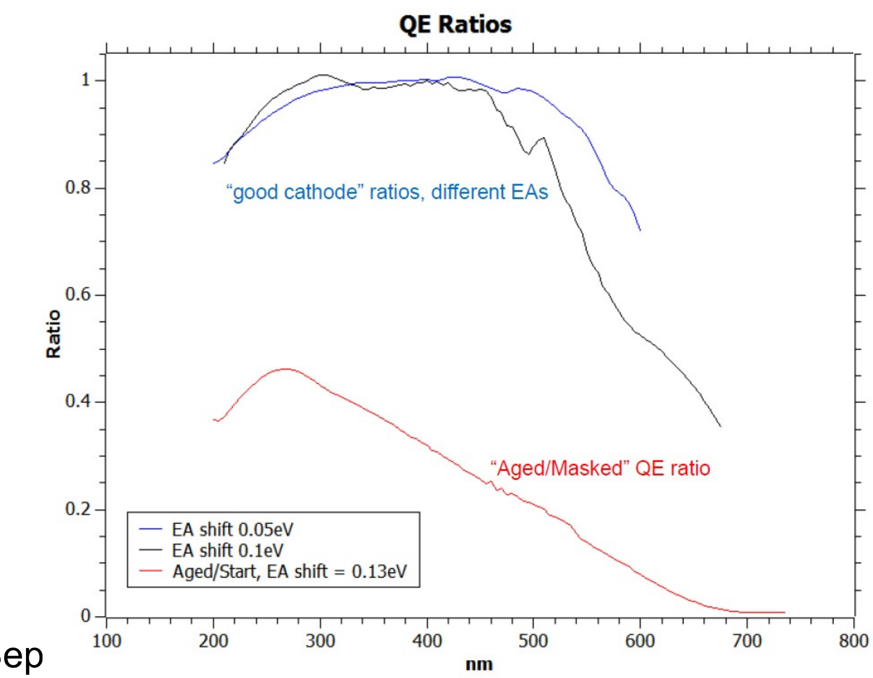
[Results from Jeff deFazio, 2016]

Aging Mechanism (Work Function?)

[Results and conclusions from Jeff deFazio. 2016]

- Work function measurements
  - Measure p.e. energy distribution curve: change in electron affinity will expand or compress the range of electron energies between threshold and hottest electrons
- Change in electron affinity (EA) seen
  - ΔEA ~ 0.13 eV
  - Very similar EDC shape → diffusive energy loss apparently unchanged
- EA impact on QE results
  - Upper curves: QE ratio of good PC side for K_2CsSb photo cathode with different EAs
  - EA drop starts at long wavelength, but has minimal impact at lower wavelengths
  - QE ratio "aged/masked" is very different → EA increase is not the main reason for aging

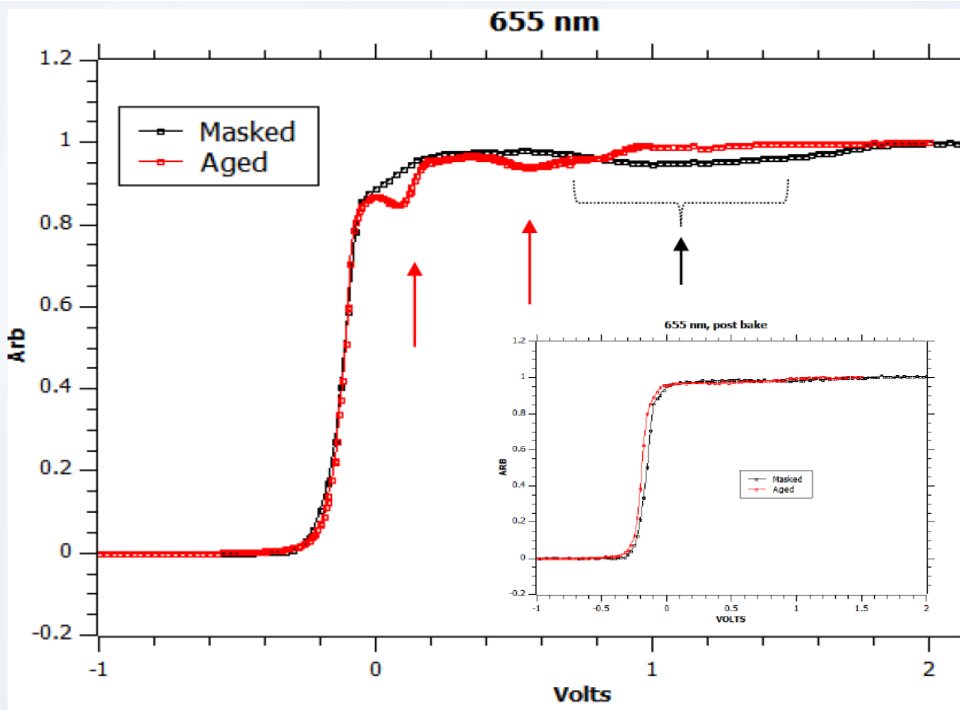




Aging Mechanism (Sputtering?)

- Electron backscattering from MCP
  - At long wavelengths the distribution of p.e. energies is very narrow → possiblity to resolve elastic scattering features at MCP surface (i.e. electrons returning to photocathode) → Cs sputtered from PC
  - Notable difference between the two PC halves (aged and masked)
  - Structures disappear after 18h at 80° C
  - But: heating also yields constant QE loss for all λ → totally different behavior than for ion feedback QE degradation

[Results and conclusions from Jeff deFazio, 2016]



- Summary
  - Bulk structure intact → band structure unchanged → photon absorption unchanged
  - Only small EA change in EDC → work function ~unchanged → p.e. escape unaffected
  - Cs ions at MCPs → sputtering from PC → cannot explain constant QE loss factor
  - **What is it then that causes the PC aging ? → answer still unclear**

Outlook

- Further investigations to understand the aging process
  - PHOTONIS XP85112 (9001223 and 9001332) are unique MCP-PMTs with an aged and an unaged half of the photo cathode (PC)
    - At PHOTONIS with non-destructive investigations of the PC
    - Maybe X-ray diffraction measurement of the PC
  - Identify the mass of the feedback ions with afterpulsing 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 potential-free picoammeter
- Setup semi-automatic quality control for MCP-PMT mass delivery

Summary

- New high-granularity 2" Hamamatsu MCP-PMT
  - Good properties, but some parameters need more tuning
  - Long tails in position distributions not understood
  - Possibility to measure Lorentz shift in B-field
- **Tremendous lifetime increase of latest MCP-PMTs** due to recent design improvements
  - **Application of ALD technique (> x50 lifetime improvement)**
  - **Huge step forward !**
  - **<u>But:</u> aging mechanism is not explained by simple work function arguments**
- Equipping the PANDA DIRCs and other high rate detectors with MCP-PMTs is feasible now

Illumination Overview

		Sensor ID	Integral charge (Aug. 15, 2016) [mC/cm^2]	QE start [%]	QE latest [%]	QE latest / QE start [%]	Comments
non – ALD	Photonis XP85112	9001223	**9234**	22.15	5.29	**24%**	Start: 23 Aug. 11 Stop: 22 Sep. 15
		9001332	**13111**	22.96	14.53	**63%**	Start: 12 Dec. 12 ongoing
		9001393	**9361**	19.05	19.49	**102%**	Start: 23 Jan. 14 ongoing
	Hamamatsu R10754X/R13266	JT0117 (M16)	**2086**	19.97	9.32	**47%**	Start: 23 Aug. 11 Stop: 24 Jul. 12
ALD		KT0001 (M16M)	**13767**	21.52	11.27	**52%**	Start: 20 Aug. 13 ongoing
		KT0002 (M16M)	**9856**	21.4	12.25	**57%**	Start: 21 Oct. 13 ongoing
		JS0022 (M64)	**1298**	17.43	14.48	**83%**	Start: 11 Dec. 15 ongoing
	BINP	1359	**3616**	11.95	9.1	**76%**	Start: 21 Oct. 11 Stop: 06 May 13
		3548	**6698**	11.93	4.58	**38%**	Start: 21 Oct. 11 Stop: 08 Jul. 15