Performance of the most recent microchannel-plate PMTs for the PANDA DIRC Detectors at FAIR

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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& the PANDA collaboration

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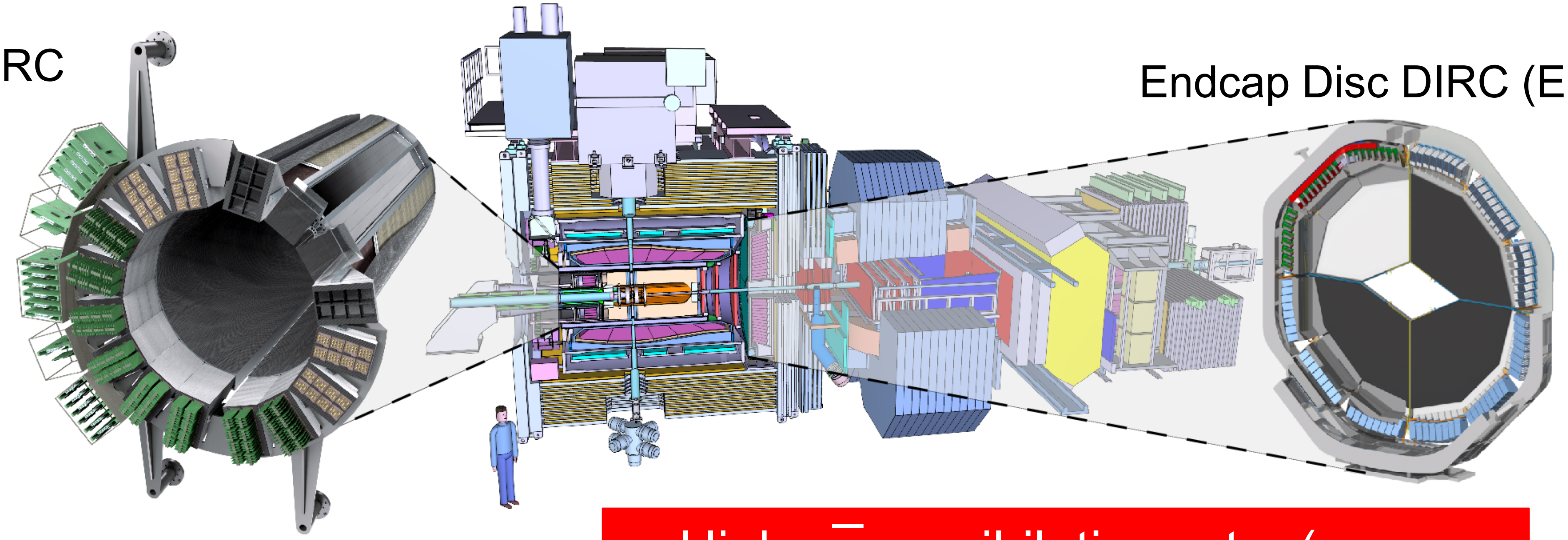
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

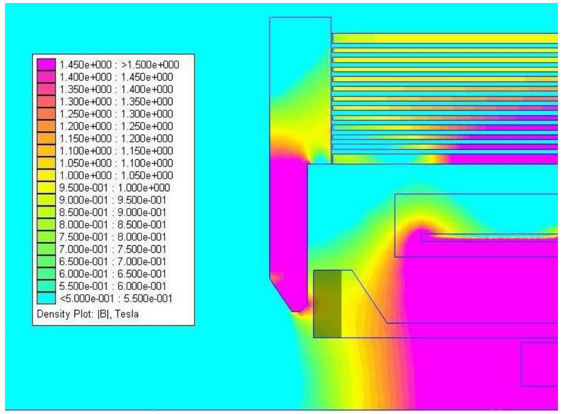
The PANDA detector at FAIR/GSI

Ref to: R. Dzhygadlo
The PANDA Barrel DIRC

Barrel DIRC

Endcap Disc DIRC (EDD)

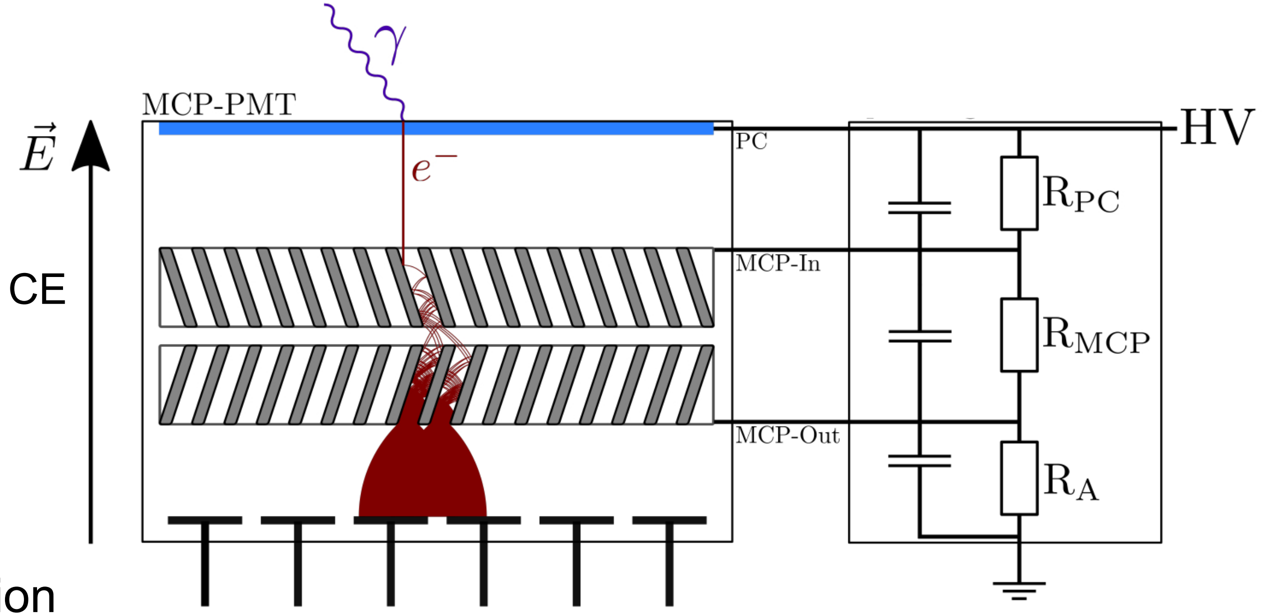




- High $p\bar{p}$ annihilation rate (average 20 MHz)
- Focal planes of both DIRC detectors are inside magnetic field
- Sensors need to operate at high magnetic field (~1 T)

MCP-PMTs for the DIRC detectors

- Sensor requirements:
  - Immunity to magnetic fields >1 Tesla
  - High quantum efficiency (QE) and collection efficiency (CE) required
    - important for experiment: detective QE (DQE) = QE · CE
  - High rate capability (<1 MHz/cm²)
  - Fast time response (σ_{RMS} ~100 ps)
  - Low dark count rate (<1 kHz/cm²)
  - Photo cathode lifetime of at least 10 years operation
  - High position resolution:
    - Barrel DIRC: ~5x5 mm²
    - Endcap Disc DIRC: 0.5x16 mm²



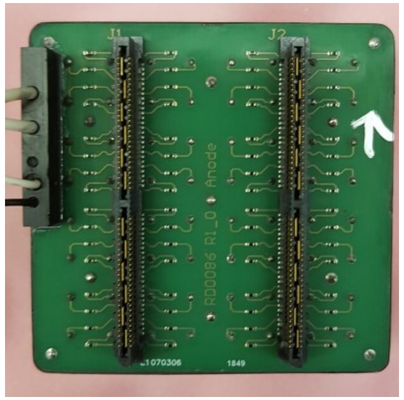
- ➢ Microchannel-plate Photomultipliers (MCP-PMTs) only viable option to fulfill all requirements
- ➢ PMTs of two vendors shown in this talk:
  - ➢ Photek (8x8 pix, 6 µm pores)
  - ➢ Photonis (8x8 & 3x100 pix, 10 µm pores)

MCP-PMTs shown in this talk

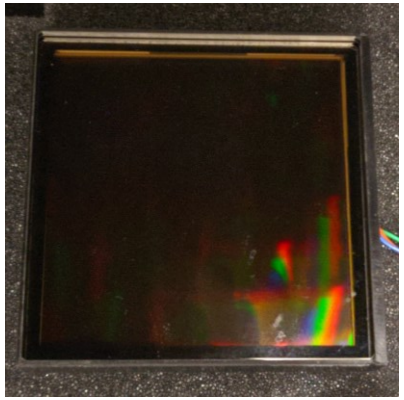
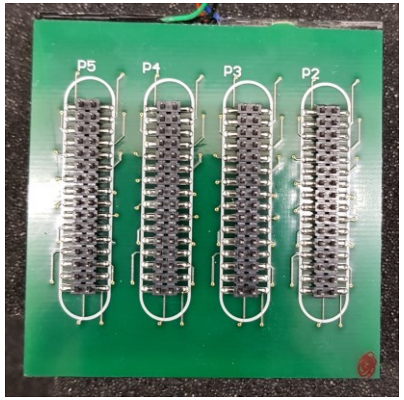
- MCP-PMTs with 8x8 pixels, 2x2 inch² active area
  - Barrel DIRC tubes from tender process (2020)
    - **Photonis 9002192**
    - **Photonis 9002193**
    - **Photek A1200107**
    - **Photek A3191220**
  - Barrel DIRC serial production tubes (2022)
    - **Photonis 9002220 – 9002224**
  - Latest Photek tubes (late 2020)
    - **A1200116**
    - **A2200606**

Ref: talk of J. Milnes

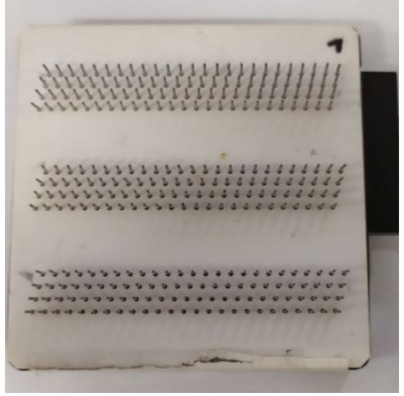
- MCP-PMTs with 3x100 pixels, tested for EDD with different internal geometry
  - **Photonis 943P541 & 946P541 (2019)**
  - **Photonis O37P541 & 105P541 (2021)**

Photonis 8x8
10 µm pores

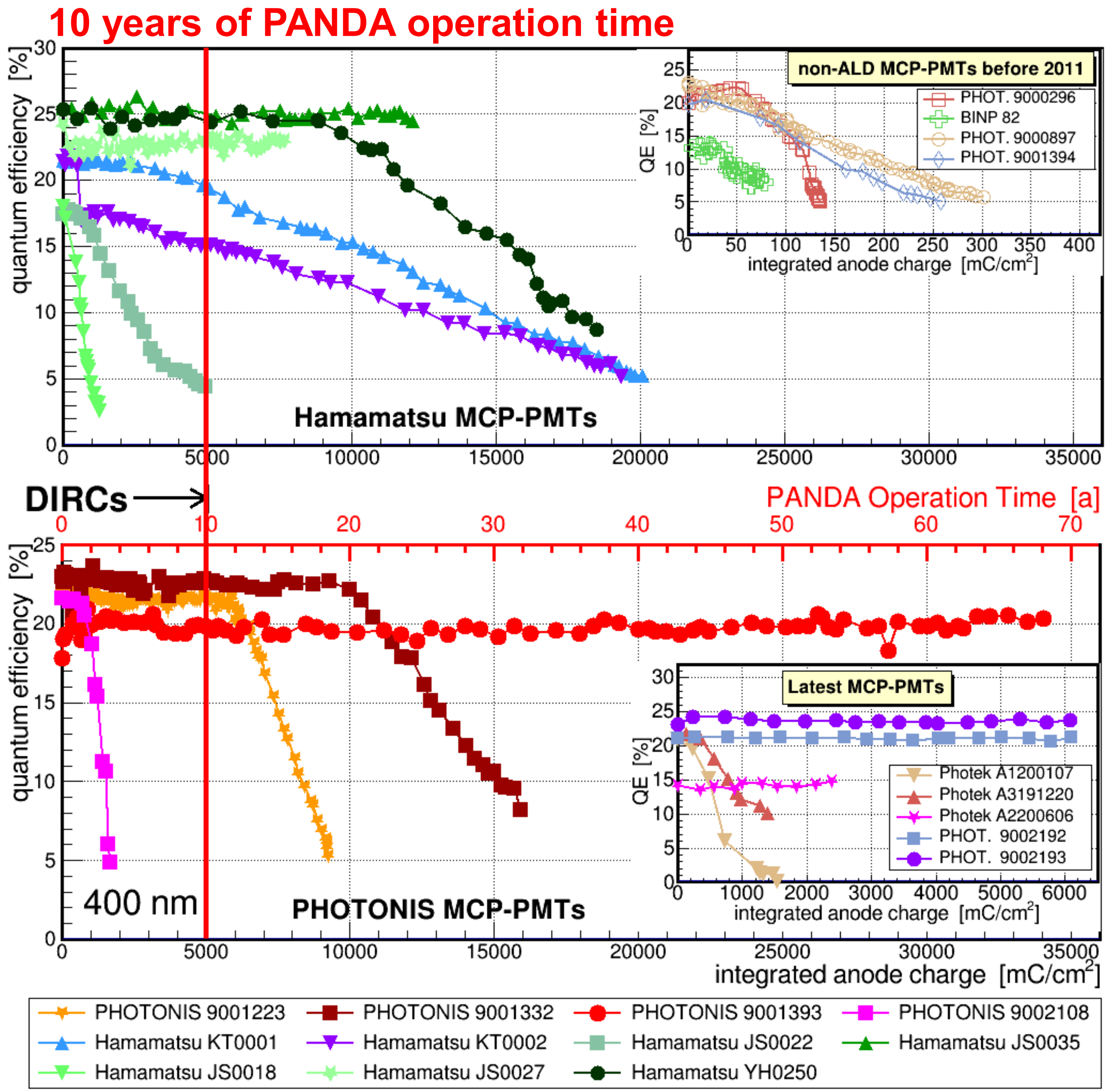
Photek 8x8
6 µm pores

Photonis 3x100
10 µm pores

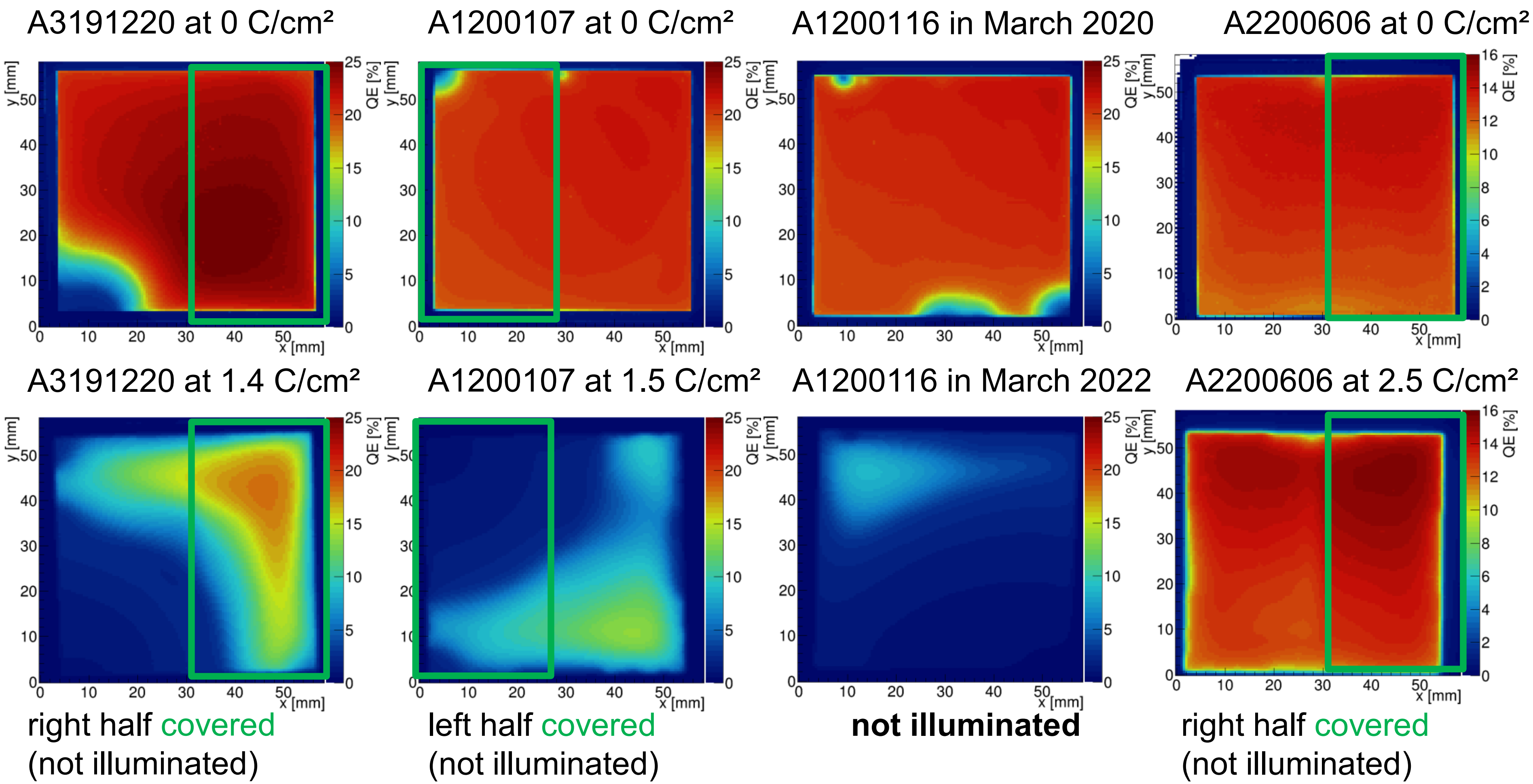
Status of lifetime measurements

- **Required spec:** 5 C/cm² IAC (10 years of PANDA) reached by most ALD-coated MCP-PMTs
- Best sensor by far: Photonis 9001393 with two ALD-layers (no QE loss up to 34 C/cm²)
- Photonis 9002108, Photek A1200107 and A3191220 had **poor lifetime**
- More information on lifetime measurements for Photek MCP-PMTs on next slide
- Photonis 9002192, 9002193 have reached **6 C/cm²** IAC without PC damage or QE loss
- Latest Photek A2200606 has no sign of QE damage up to **2.5 C/cm²**



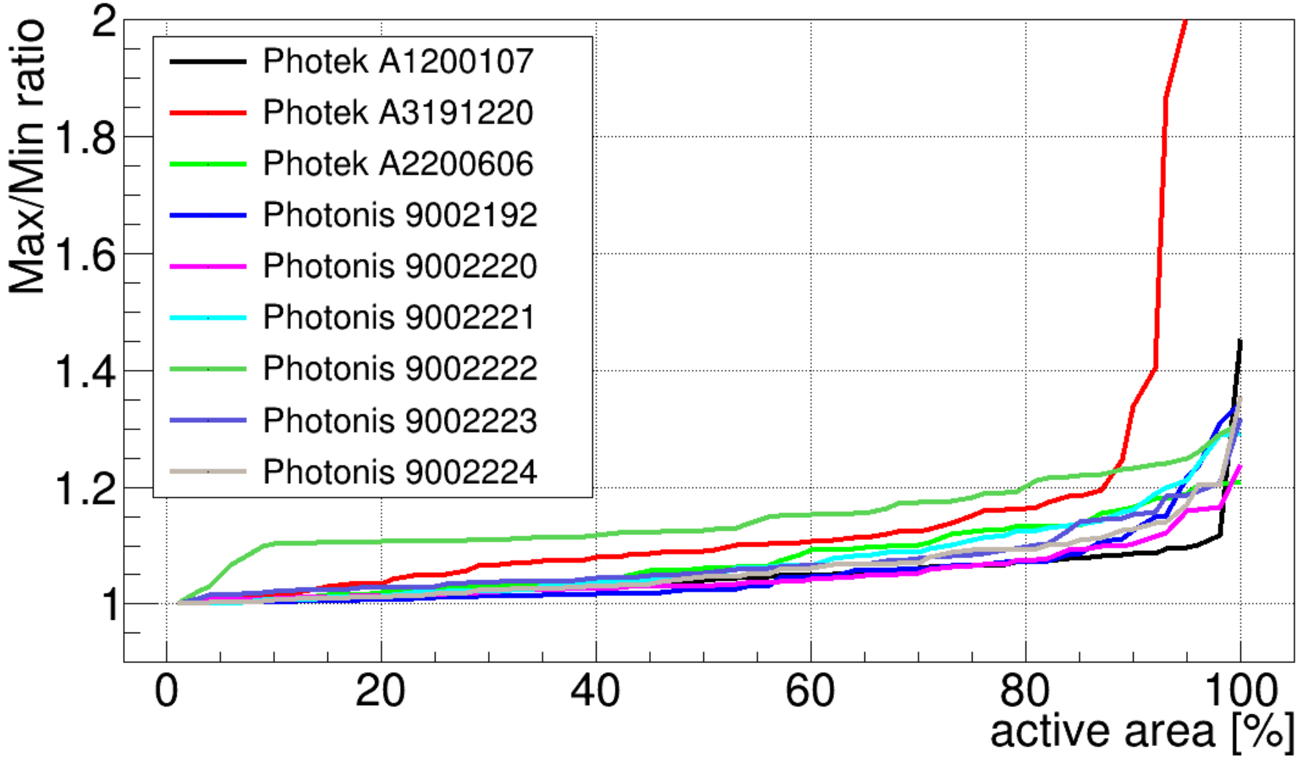
Photek - lifetime issues and improvement

- First Photek tubes had decreasing QE from the beginning even without illumination, probably caused by vacuum microleaks
- QE damage starts to grow from bad spots
- Problem seems to be solved with A2200606

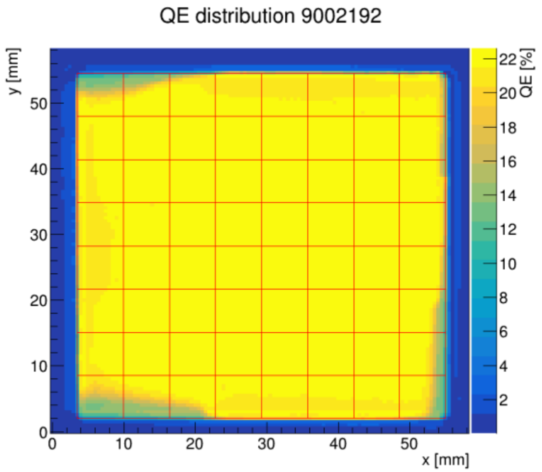


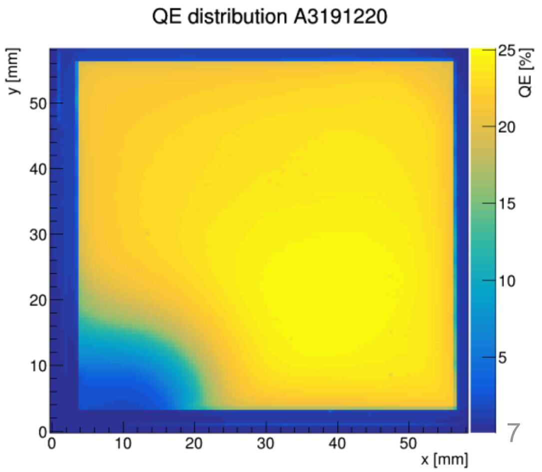
Quantum efficiency (QE)

- **Required spec:** max/min ratio <1.5 over whole active area
- Evaluation of max/min ratio:
  - Divide active area into 8x8 pixels and calculate mean QE of every pixel
  - Mean QE of pixel with max. value divided by mean QE of every other pixel gives max/min ratio
  - Plotted in order from best to worst pixel



- All Photonis tubes fit requirement of QE homogeneity
- Photek A3191220 exceeds limit due to initial microleak which caused QE damage at the corner (as seen on bottom right)

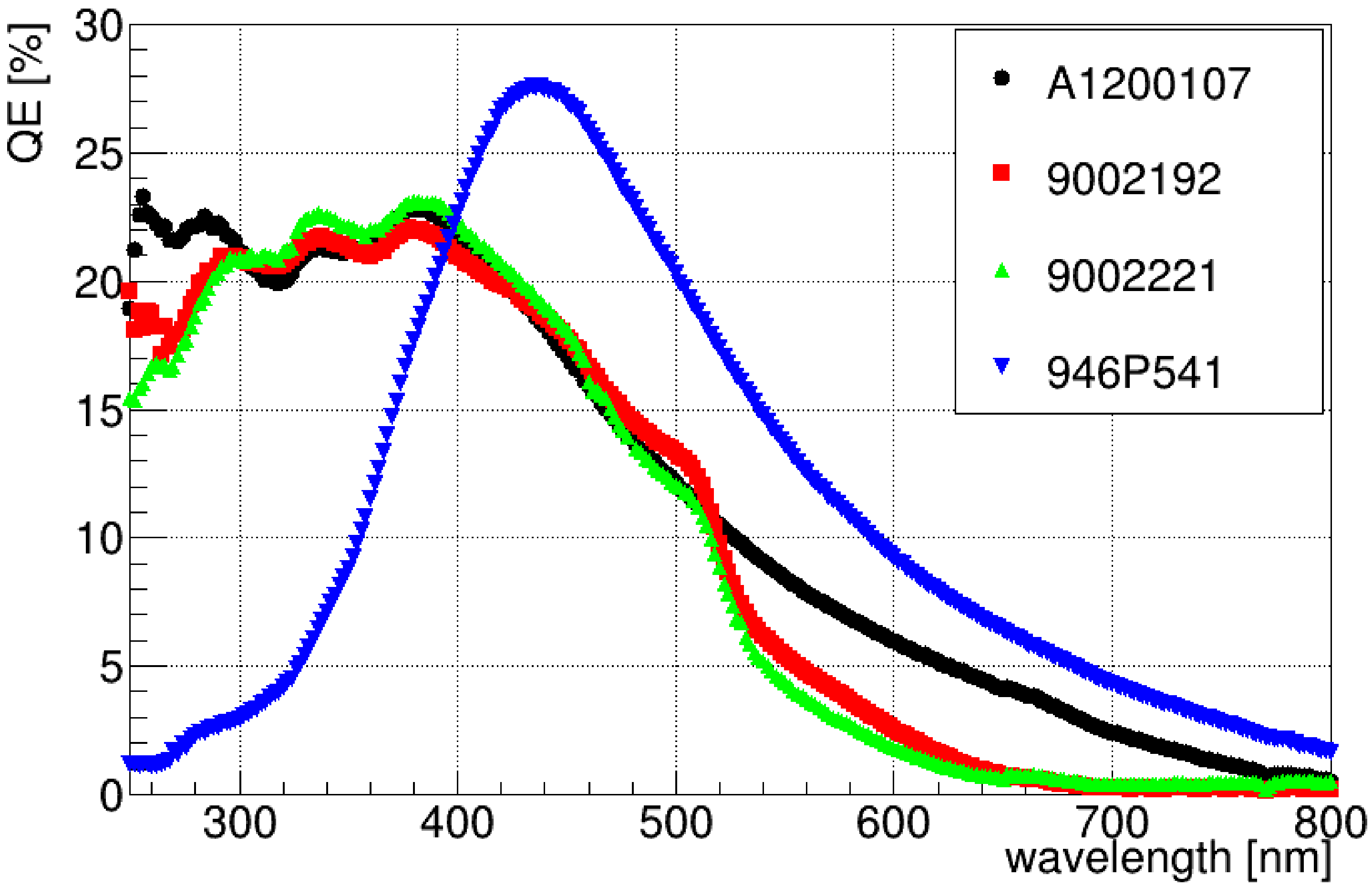




QE vs wavelength

- **Required spec:** peak QE of >18% between 300 – 400 nm
- QE measured at center pixel
- Peak QE of all 8x8 pixel tubes at about 380 nm

- QE distribution over wavelength for Photonis 946P541 different because of modified photo cathode (blue enhanced) → maximum shifted



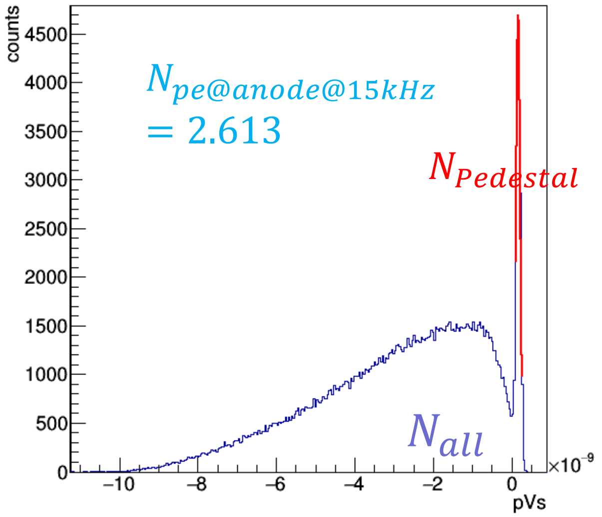
Collection efficiency (CE) measurement

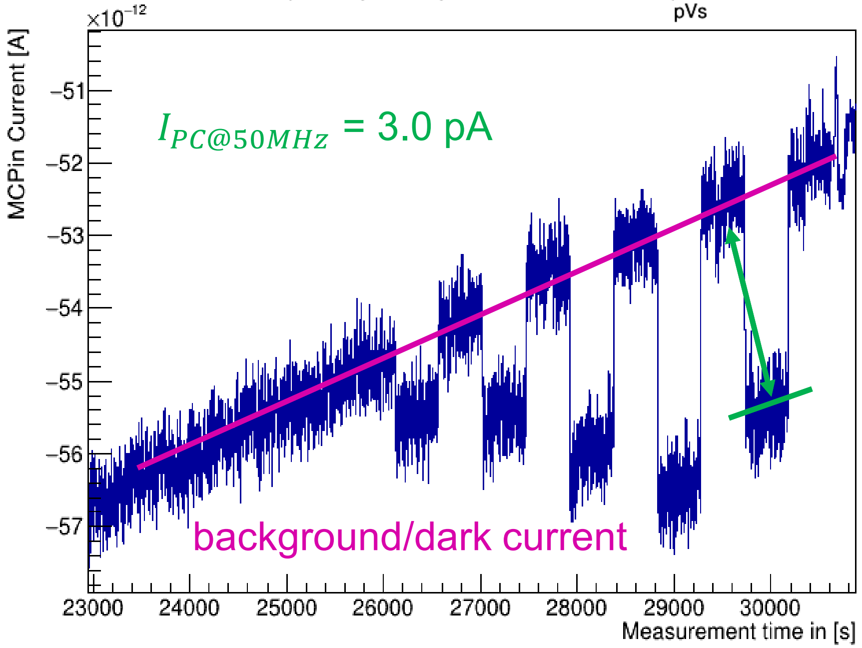
- CE is the probability that a photoelectron creates a signal at the anode (losses due to missing the MCP pore / absorption, …)
- Measurement of $\mathrm{CE} = \mathrm{N}_{\mathrm{pe@anode@15kHz}} \,/\, \mathrm{N}_{\mathrm{pe@PC@15kHz}}$
- Numerator is simple: Poissonian statistics of charge spectrum (measured with a Picosecond Laser (PiLas) at 15 kHz and a ND-filter)

➢ $\mathrm{N}_{\mathrm{pe@anode@15kHz}} = -\ln(\mathrm{N}_{\mathrm{Pedestal}}/\mathrm{N}_{\mathrm{all}})$

- $\mathrm{N}_{\mathrm{pe@PC@15kHz}}$ can only be measured indirectly:
  - Measure MCPin current using the QE setup at several high laser frequencies
  - Correct for non-linearities in the intensity vs frequency relation of the laser by using a reference diode

$$\mathrm{CE} = \frac{\mathrm{N}_{\mathrm{pe@anode@15kHz}} \cdot e \cdot 50\mathrm{MHz}}{\mathrm{I}_{\mathrm{PC@50MHz}}} \cdot \frac{\mathrm{I}_{\mathrm{Diode@50MHz}} \cdot 15\mathrm{kHz}}{\mathrm{I}_{\mathrm{Diode@15kHz}} \cdot 50\mathrm{MHz}}$$





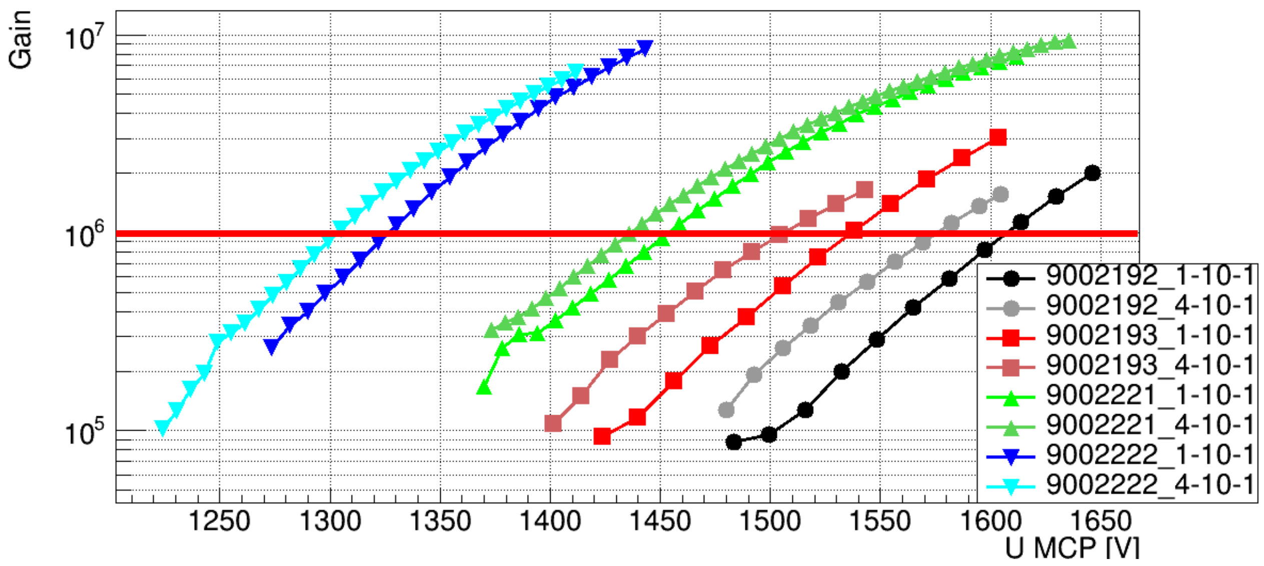
CE results

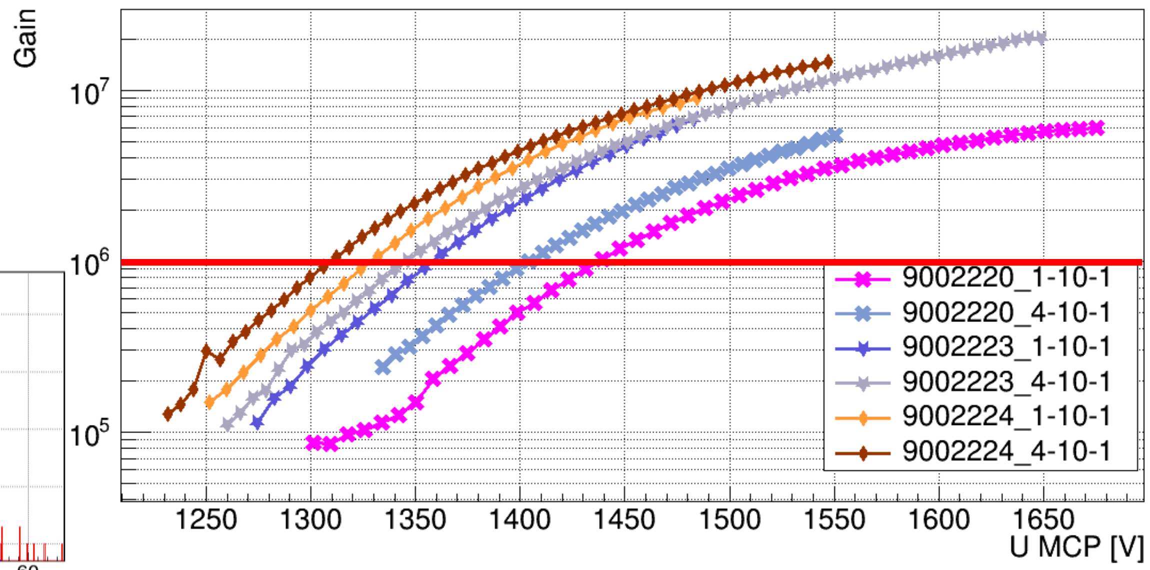
Tube	Photonis XP85112 9001394	Hamamatsu R13266-07-M64 JS0022	Hamamatsu R13266-07-M64-M YH0250	Photonis XP85112 9002108	Photek MAPMT253 A1200116	Photonis XP85112 9002220
Year of production	2013	2014	2017	2018	2020	2022
Properties	non-ALD	ALD, **film in front of MCPs**	ALD, no film, most recent	ALD, first **Hi-CE**	ALD	ALD, **Hi-CE**
CE	(63 ± 6)%	(39 ± 4)%	(65 ± 7)%	(95 ± 9)%	(90 ± 9)%	(95 ± 5)%

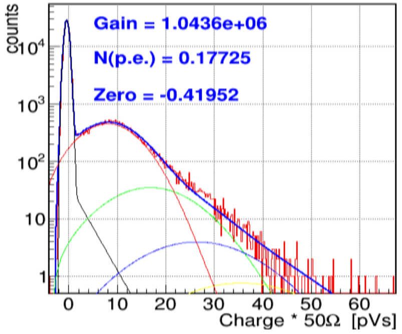
- ~65% for former standard Photonis tube 9001394 seems reasonable
- Photonis 9002108 was first Hi-CE tube received and measured
- Photonis 9002192 and 9002193 also contain Hi-CE MCPs and have ~88% CE
- All Photek MCP-PMTs have quite high CE (>75%)
- Ion feedback protection film in Hamamatsu tube significantly reduces CE
- New Photonis tubes 9002220 – 9002224 reach CE of 80 – 90%

Gain vs voltage for recent Photonis MCP-PMTs

- Measurement of gain curve:
  - Measure charge spectra for different voltages
  - Fit charge spectra measured with scope
- Measurements with two different voltage dividers taken for each tube
  - 1-10-1: 200 V PC - MCPin
  - 4-10-1: 800 V PC - MCPin
- All 4-10-1 curves at slightly higher gain than other curves because of higher initial energy of photo electron
- Gain of 10^6 safely reached by all tubes, for a few most recent ones even > 10^7
- Maximum applicable MCP voltage for all Photonis tubes: 1800V

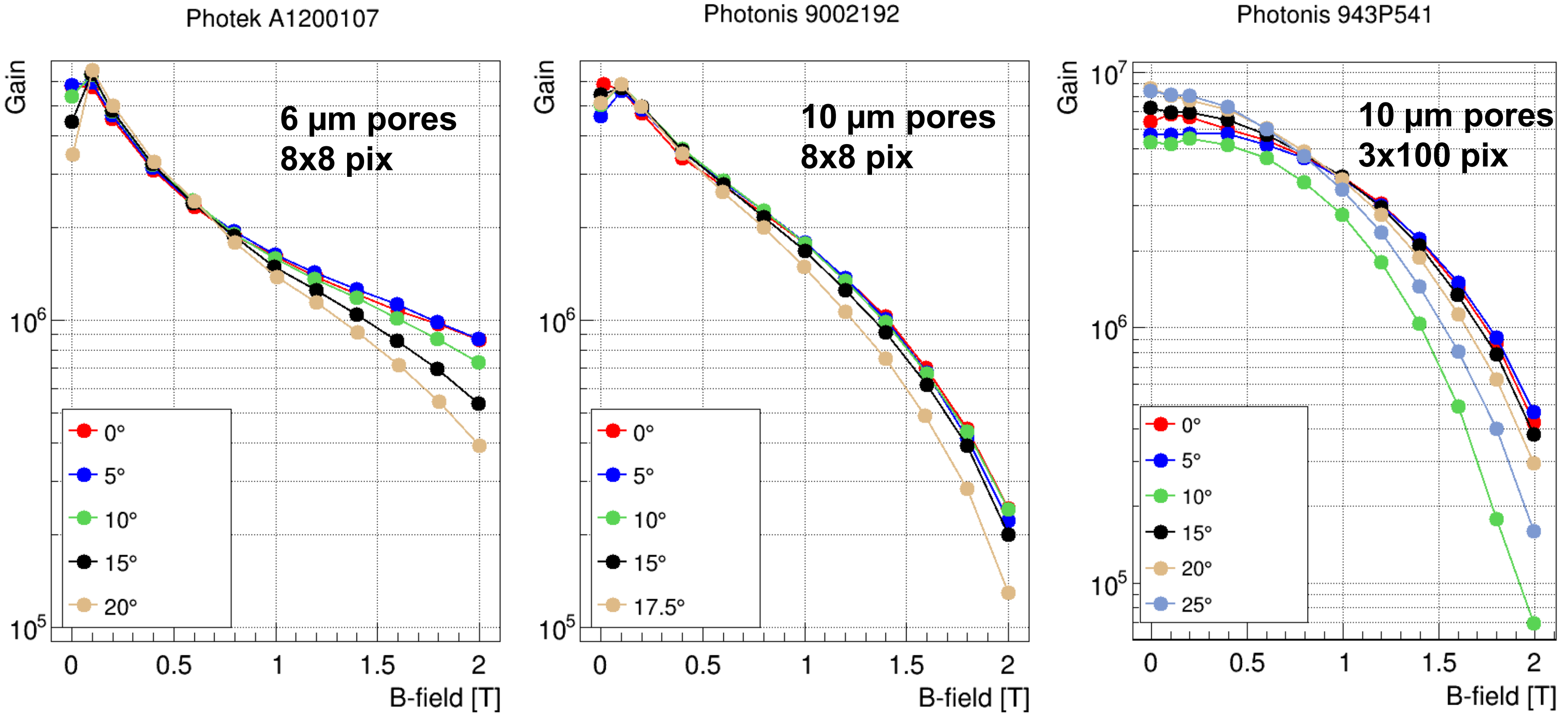






Gain dependency in B-field

- Photek tubes: 6 µm MCP-pore diameter
- Photonis tubes: 10 µm MCP-pore diameter
- Similar behaviour of 8x8 pixel tubes **up to 1 T, gain loss factor of ~3 for all tubes**
- Significantly lower gain loss at higher field strengths for Photek tubes
- Different internal geometry of 8x8 & 3x100 pixel Photonis tubes → different slopes and lower gain loss for fields up to 1 T

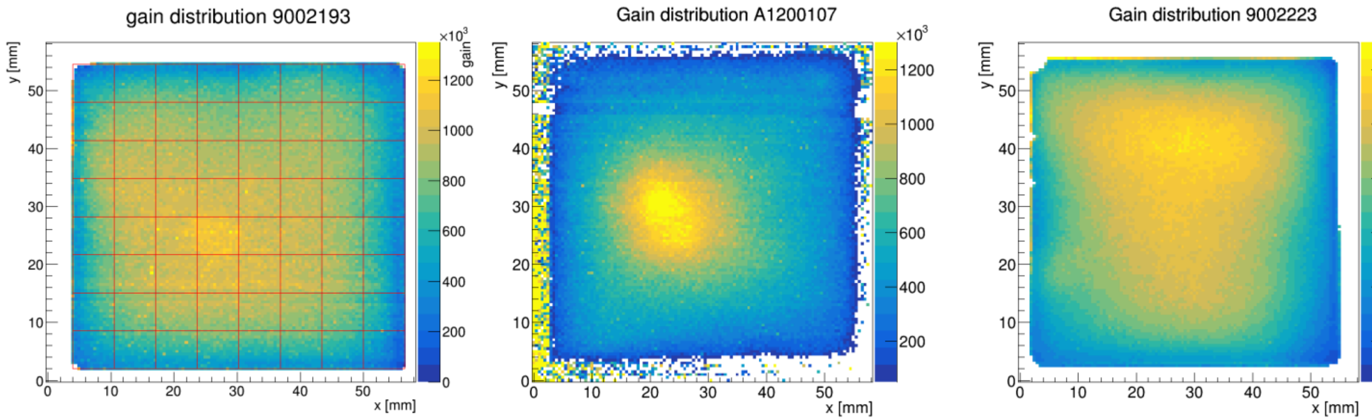


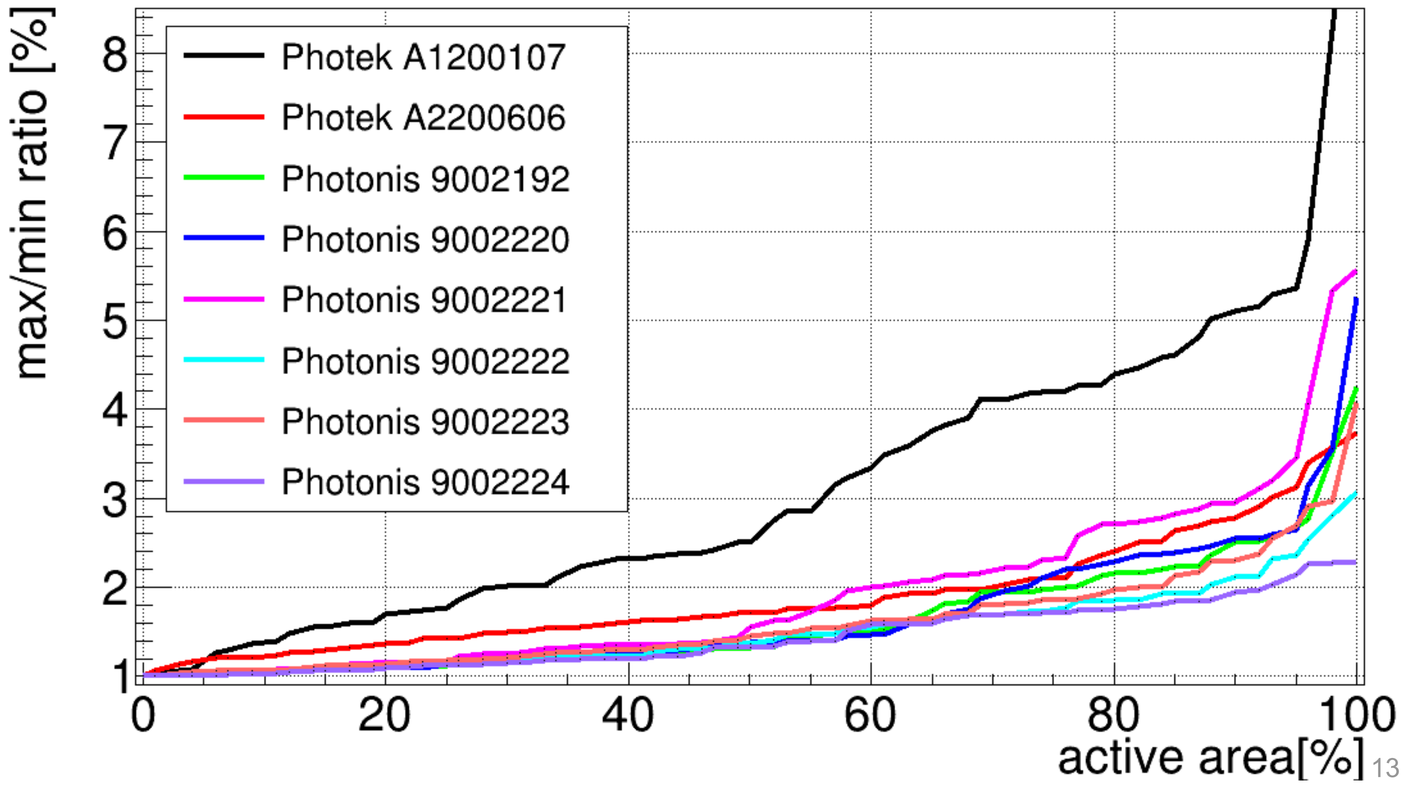
Gain loss [1/x]:

Tube	0 – 1 T, 0°	1 – 2 T, 0°	1 T, 0° - max°	2 T, 0° - max°
A1200107 (8x8 pix)	3.3	2.0	1.3	2.9
9002192 (8x8 pix)	3.3	~20	1.2	3.1
943P541 (3x100 pix)	2.2	~22	1.3	6.4

Gain homogeneity

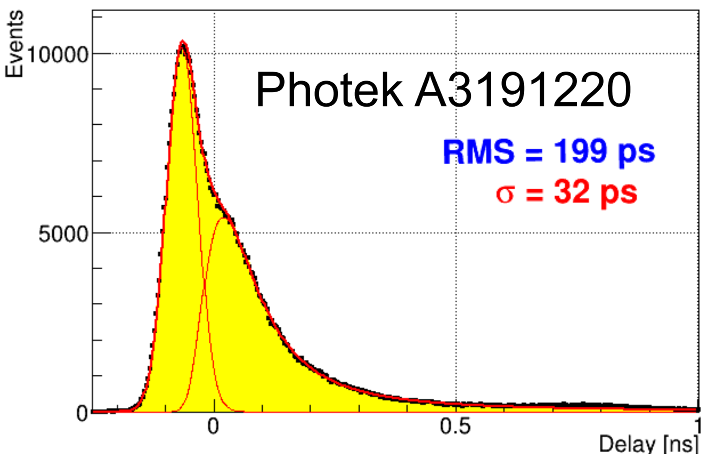
- **Required spec**: max/min ratio <3 over whole active area
- All Photonis tubes and latest Photek A2200606 are below max/min ratio of 3 for **at least 90%** of active area
- Overall homogeneity ratio is within specs for Photonis tubes
- Photek A1200107 ratio: ~5.5 at 95% active area
- Photek A1200107 less than 60% below required ratio
- Improved homogeneity for latest Photek A2200606 (below 3 for 90% of active area & below 4 in total)



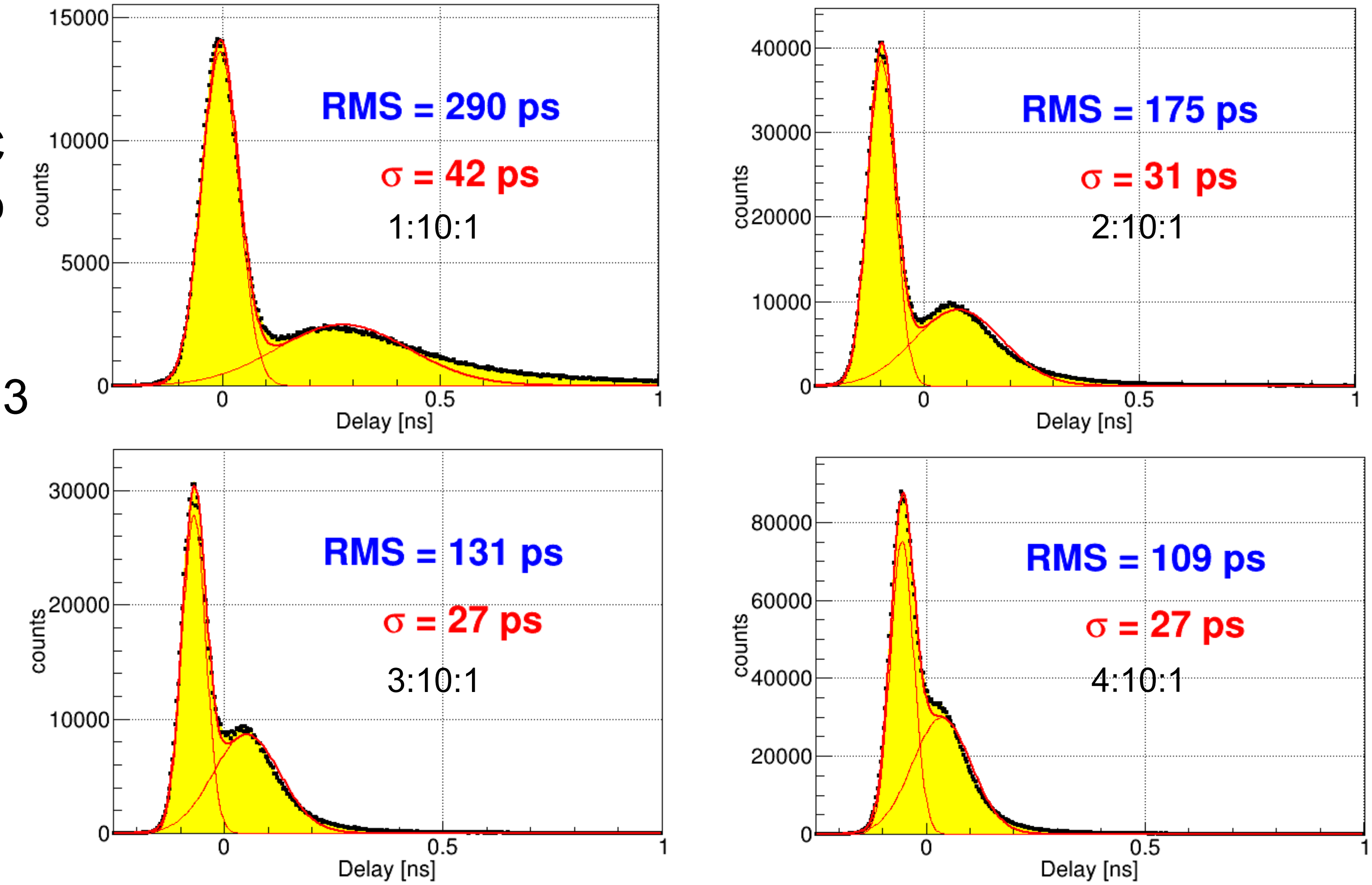


Time resolution

- Higher CE of Photonis comes with a price: more collected recoil electrons → worse time resolution (especially RMS!)
- Solution: increase of HV between PC and MCPin → shift of recoil peak into the main peak → better TTS (σ) and RMS (-0.5…2 ns)
- RMS timing improves by a factor 2 – 3

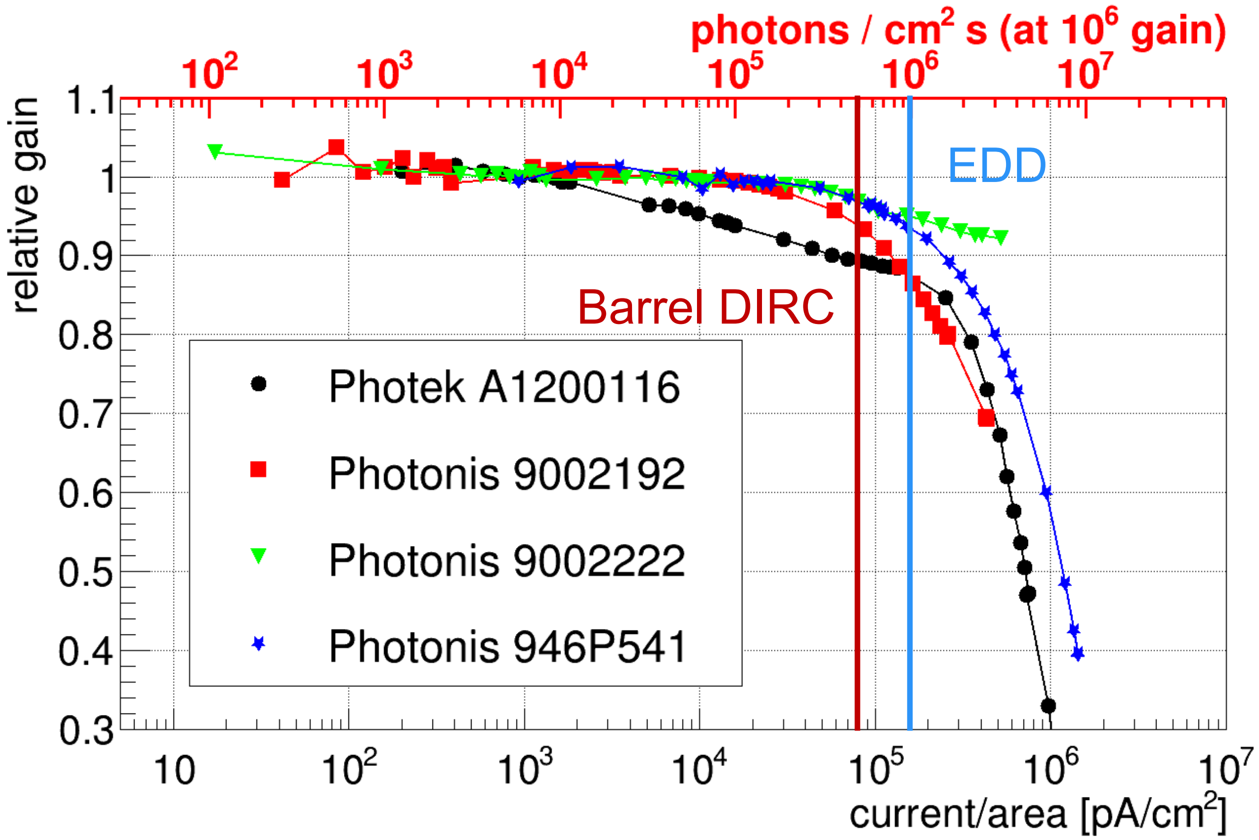


Photonis 9002193 with different voltage dividers, from 1:10:1 (PC-MCPin:MCPin-MCPout:MCPout-Anode) to 4:10:1



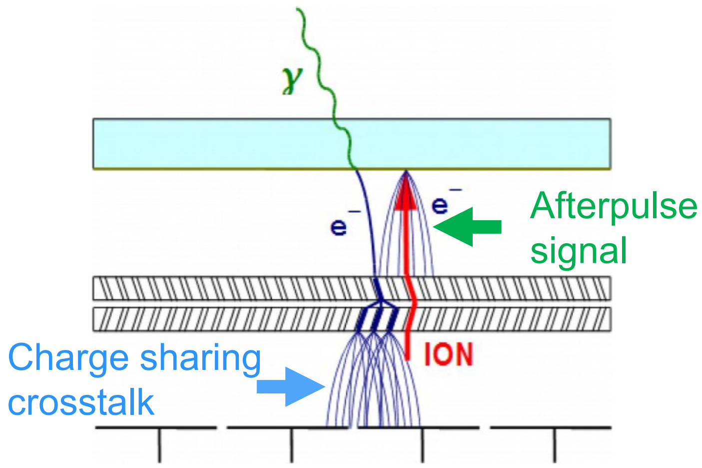
Rate capability

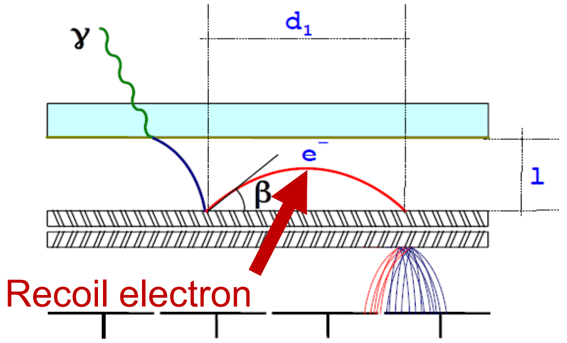
- Sublinear increase of anode current with increasing light intensity from laser
  → MCP-PMT gain saturates
- **Required spec:**
  - Barrel DIRC: <20% gain loss @ 0.5 MHz photons/cm²
  - EDD: <20% gain loss @ 1 MHz photons/cm²
- All shown tubes reach requirements
- Latest Photonis tubes (9002222) indicate an improved rate capability compared to older ones (9002192)
- Photonis 9002222 reaches about 4 MHz photons/cm² with gain loss <10%

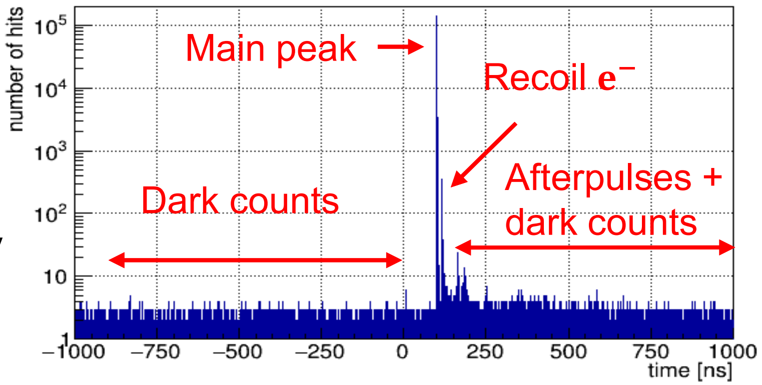


TRB/DiRICH DAQ system

- Multihit capable DAQ system used in HADES and planned for Barrel DIRC applied to simultaneously read out all MCP-PMT channels
- Each channel: TRB/DiRICH system is permanently analysing data stream and buffering time and time-over-threshold (ToT) information for each hit
- After a trigger (laser) (t = 100 ns) all hits within a certain time interval (-10 to +1 µs) are read out and stored
- Main information obtained for each channel with xy-scans:
  - x-, y-position, hit time, ToT, number of hits
- Higher level information deduced (currently):
  - Afterpulse distributions → TOF of feedback ions
  - Dark count xy-distributions
  - Charge sharing crosstalk (≥2 hits at same time on neighbouring channels)
  - Recoil electron distributions → back bouncing electrons at MCP entry (spatial information and time delay)

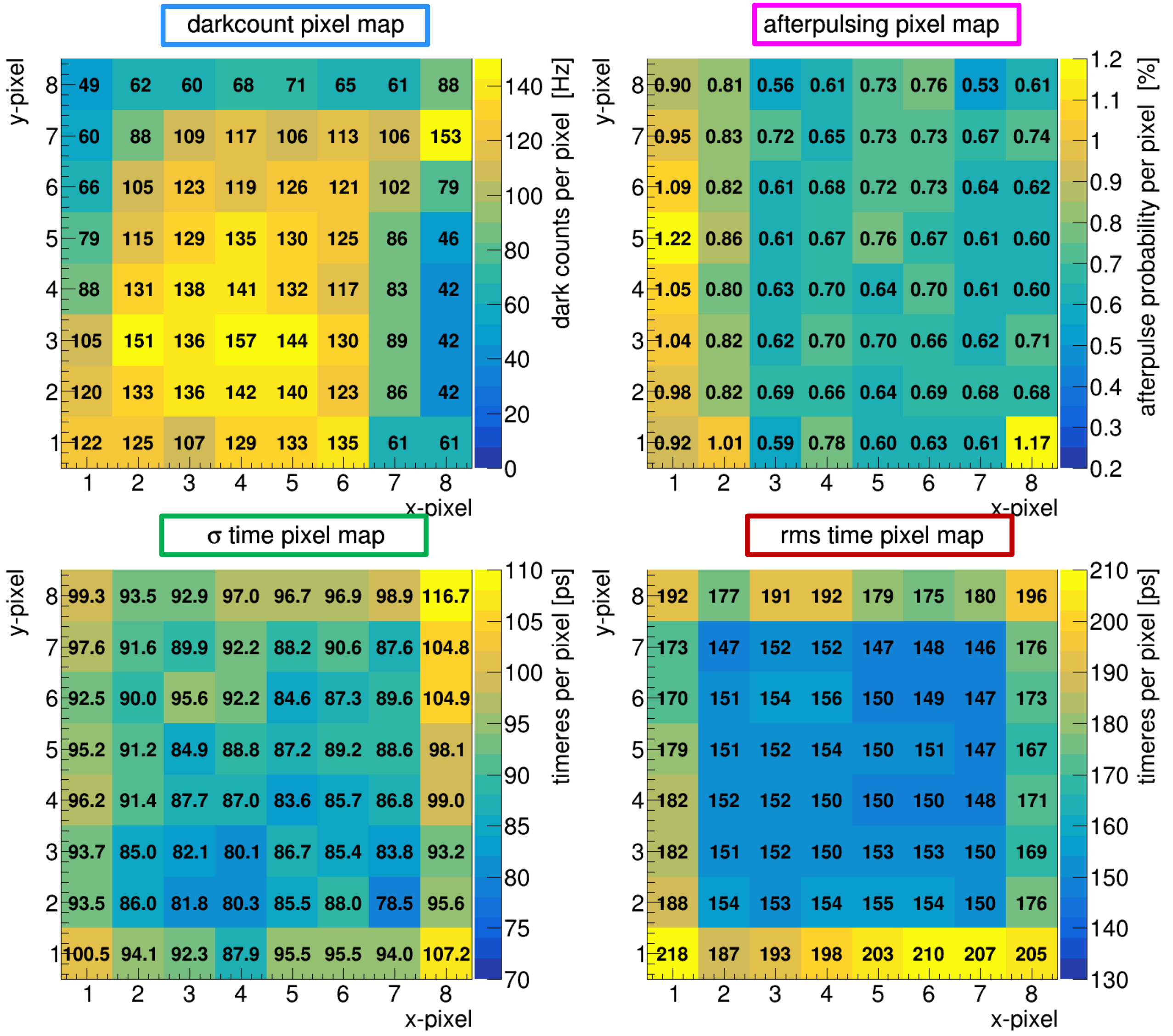






TRB surface scan results - Photonis 9002223

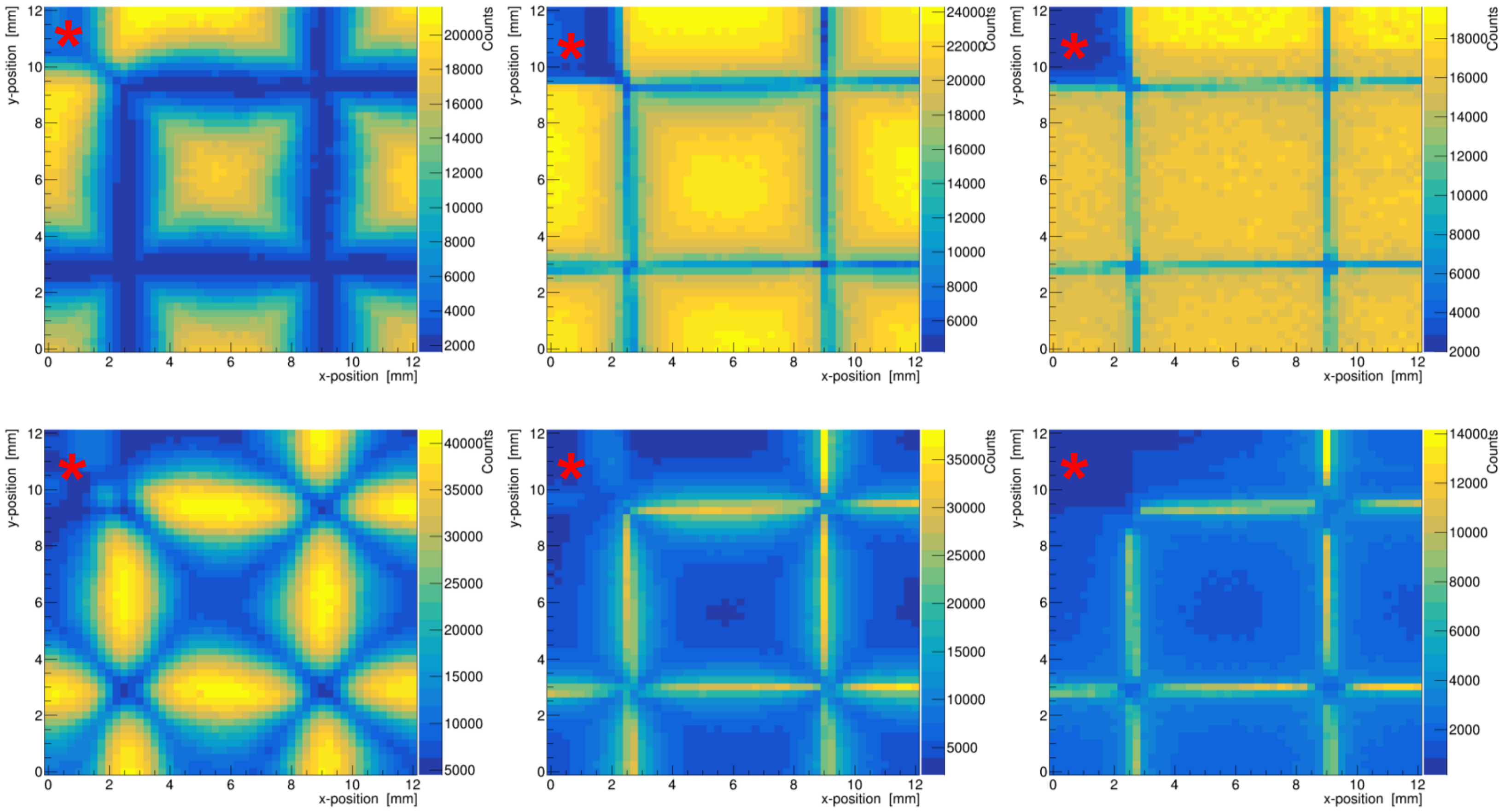
- Scan over whole active area with 0.5 mm step size & 20% single photon peak (spp) threshold
- Pixel map shows low darkcount rate per pixel
- Afterpulse ratio for most pixels below 1%
- σ and RMS time resolution not directly comparable with time resolution shown before because:
  - Combined resolution of tube and DAQ electronics
  - Measured mean of different position at a pixel (runtime difference over pixel size)
- Worse RMS and σ resolution at outer pixel ring
- Mean σ: **92 ps**
- Mean RMS: **166 ps**
- AP: **0.74%**
- DCR: **104 Hz/pixel (247 Hz/cm²)**



Photonis 9002192 charge sharing crosstalk

- Top row 1 hit events plotted
  - <2 mm charge cloud width at 0 Tesla
  - Visible pixel structure
  - For higher B-field strength pixel definition gets sharper due to decreasing charge cloud width
- Bottom row 2 hit events plotted
  - Visible pixel rim structure
  - Charge sharing has less spatial spread with increasing B-field strength
  - Pixel rims get sharper

20mT | 200mT | 1000mT

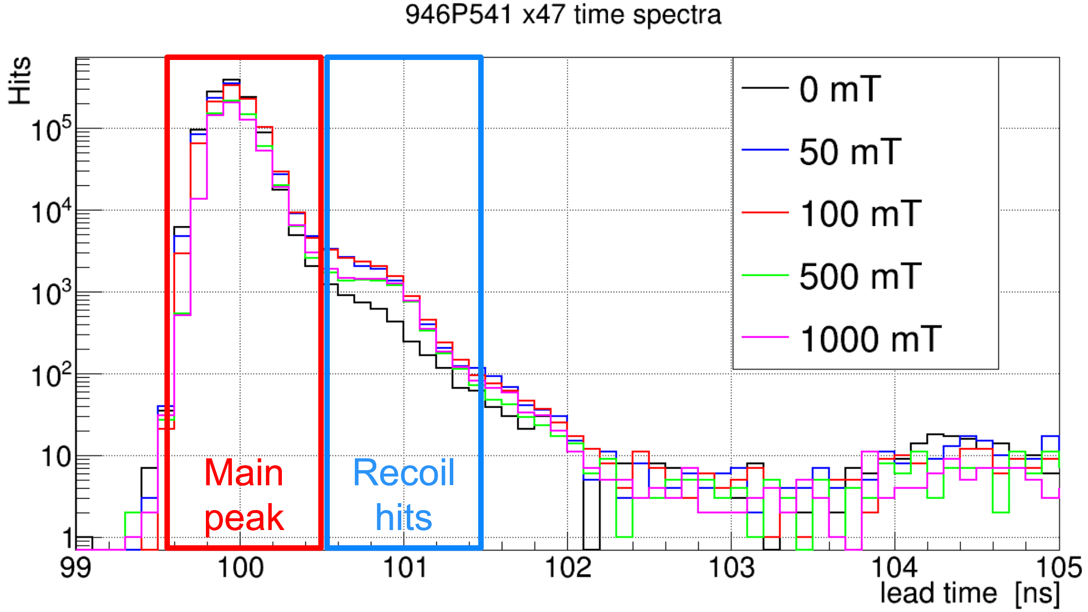


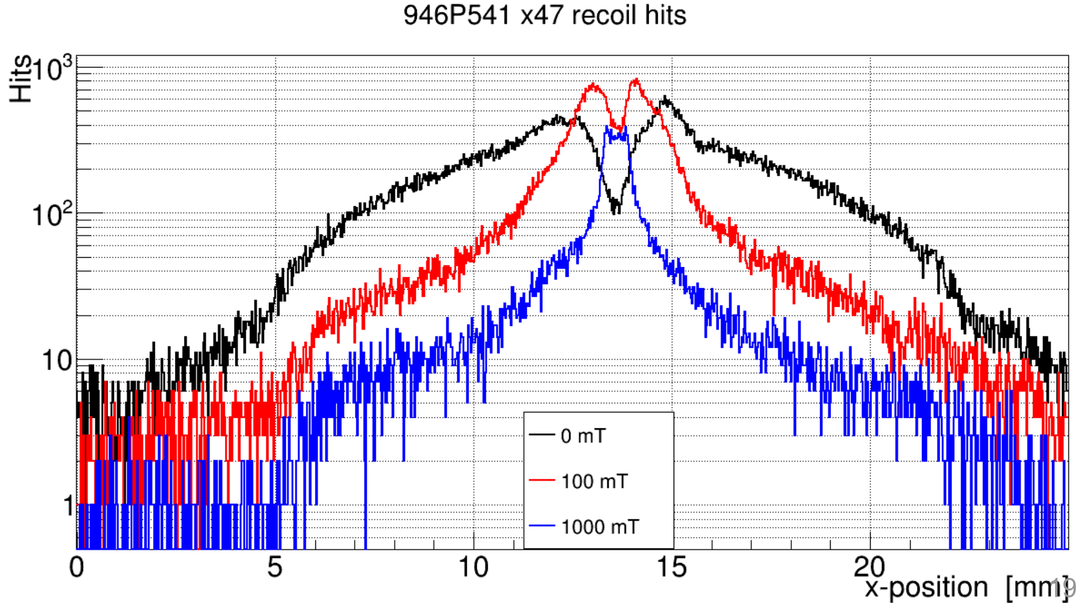
*Dead DAQ readout channel

<2 mm charge cloud width at 0 Tesla

Photonis 946P541 recoil distribution

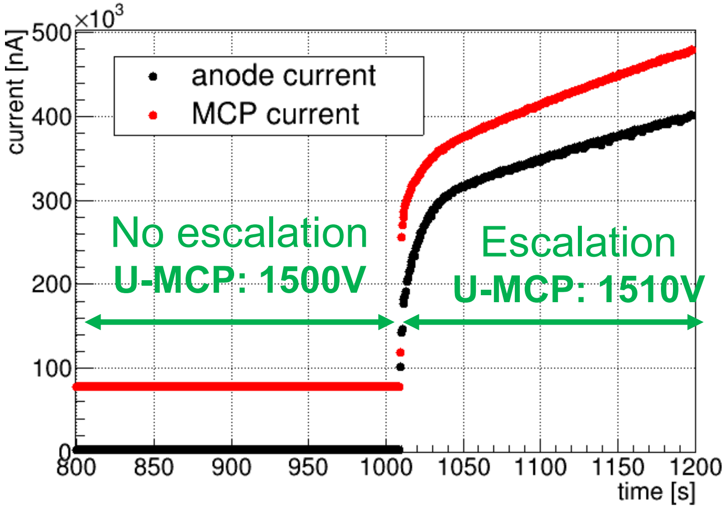
- Top: time spectra for different B-fields from 99 – 105 ns (main signal peak & recoil electrons)
- Only minor changes in time distribution for recoil hits
- Bottom: spatial distribution of recoil hits (hits in time window from 100.6 – 101.5 ns, inside blue box) for varying B-field
- Spatial spread shows strong dependence
  - >10 mm recoil electron spread at 0 T
  - At higher fields recoil electrons much closer to pixel
  - Better position resolution



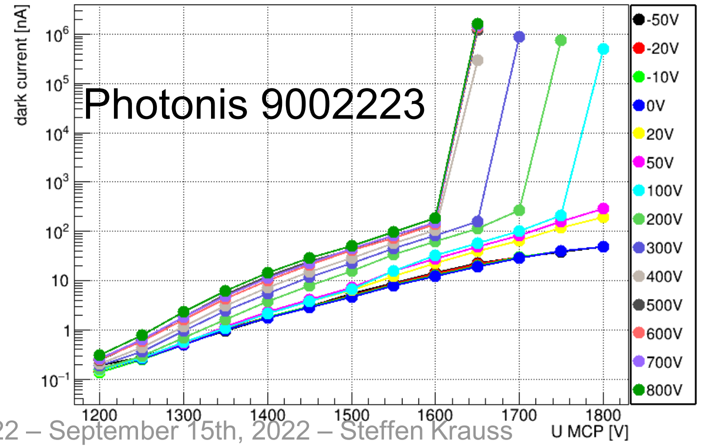


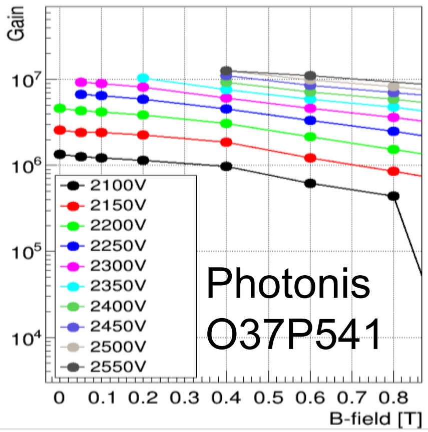
“Escalation“ behaviour

- B-field measurements showed strange effects (“escalation“) when decreasing field to 0 T, first observed in fall 2020
- Start of “escalation“ depends gain and/or illumination conditions
- List off effects seen during “escalation“:
  - Higher current across the MCPs (factor >3) → resistivity drop
  - Seems to have no equilibrium state, steady increase of currents
  - High (dark) count rate and high anode current
  - Smaller signals → gain drop
  - **photon creation**
  - Effects appear to be less serious inside magnetic field
- Escalation behaviour only appears with latest Photonis tubes
  - By optimizing the ALD process Photonis was able to shift the ”escalation” starting point to higher gains, but it is not yet completely gone



Reason: photon creation inside the MCP-PMT, can be seen with camera or even bare eyes





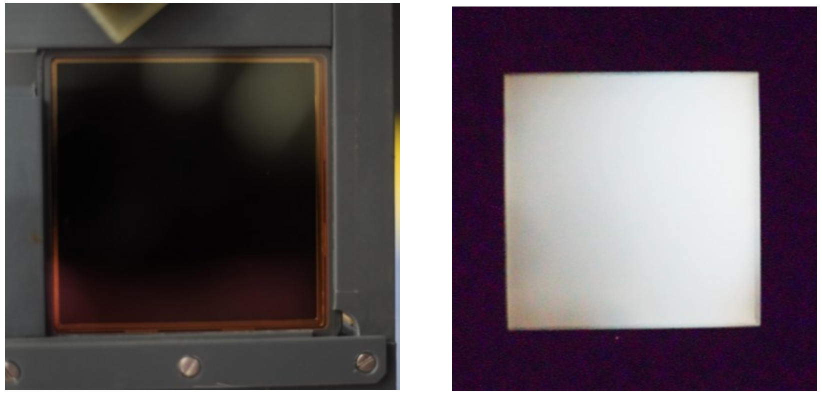


photo of PMT before operation and during escalation mode

Overview of other performance parameters

Parameter	Required for Barrel DIRC	Photek MA-PMT253 A1200107	Photek MAPMT253 A3191220	Photek MA-PMT253 A2200606	Photonis XP85112 9002192	Photonis XP85112 9002193	Photonis XP85112 9002220	Photonis XP85112 9002223
dark count rate	<1 kHz/cm²	165	16	908	32	157	1700	247
TTS	≤50 ps	40	36	33	26	27	41	Not measured
RMS timing precision	<150-200 ps in -0.5…+2 ns	215	199	177	109	109	105	
rate capability	max 10% gain loss at 0.5 MHz/cm²	0%	0%	Not measurable	8%	7%	10%	4%
DQE	≥12%	23%	18%		20%	22%	19%	17%
QE uniformity (max/min)	better than factor 1.5	1.92	8.33	1.21	1.28	1.35	1.23	1.32
gain uniformity (max/min)	better than factor 3	7.7	12.5	3.1	4.2	3.1	4.8	4.2

Summary

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- Lifetime of Photonis 9002192 & 9002193 reached 6 C/cm² (12 years of PANDA) without QE damage, latest Photek A2200606 has reached 2.5 C/cm²
- PANDA Barrel DIRC requirements fulfilled by latest tubes
- Latest Photek A2200606 tube shows significant improvements of QE and gain uniformity and also lifetime
- “Escalation“ is a problem which needs to be further investigated
  - Entering of escalation mode starts at higher gains with increasing magnetic fields
  - Production of photons
  - After communication of the effect to Photonis they have optimized the ALD process
  - ➢ effect reduced but not completely gone yet
- Mass production and quality assurance measurements of 155 MCP-PMTs for Barrel DIRC have started

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