Experience with MCP-PMT Studies

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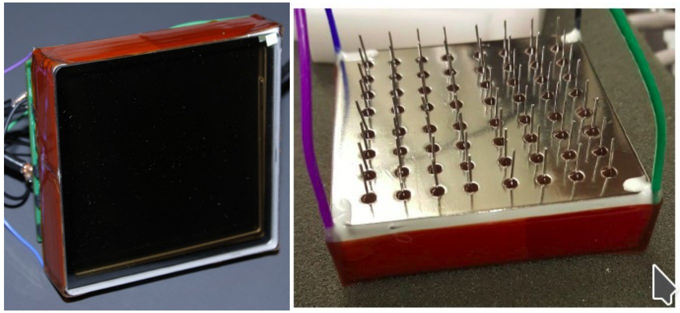
- Types of latest MCP-PMTs studied
- Quantum and collection efficiency (QE, CE)
- Gain (with and without B-field)
- 3-axis stepper and homogeneity measurements of QE and gain
- Measurement of time resolution and rate capability
- "Escalation"
- Lifetime measurements
- Combination of 3-axis stepper with DiRICH/TRB3 DAQ for quality control measurements of Photonis MCP-PMTs
- Measurement of DCR, recoil electrons, afterpulses and crosstalk

Latest tested 2-inch Multi-Anode MCP-PMTs

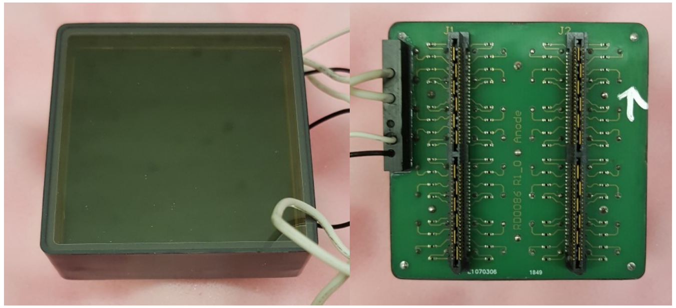
Hamamatsu R13266

- first prototypes (2014) with 1-layer ALD coating + film in front of 1st MCP
  → poor collection efficiency (CE)
- latest versions are without a film to improve P/V ratio of pulse heights
  → **normal CE (~65%)**
- available as 8x8 and 6x128 anode array
- active / total size: 51x51 / 61x61 mm^2
- **active area ratio: 70%**
- pore size: **10 µm**
- very expensive!



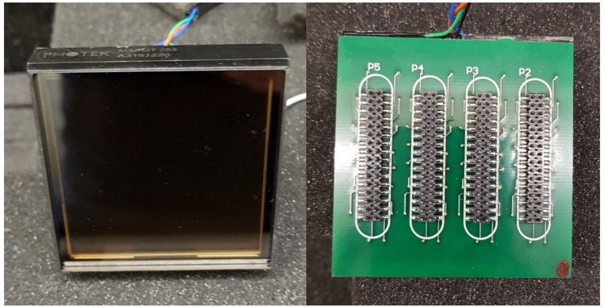
Photonis XP85112

- layout existent since Burle Planacons
- 1- **(and 2-)layer** ALD coatings; no film
- available as 8x8 and 3x100 anode array
- active / total size: 53x53 / 59x59 mm^2
- **active area ratio: 81%**
- pore size: **10 µm** (and **25 µm**)
- latest models with improved backplane to reduce oscillations and crosstalk
- improvements to catch most electrons bouncing back at MCP-in → **CE > 90%**
  - D. Orlov et al., JINST 13 (2018) C01047

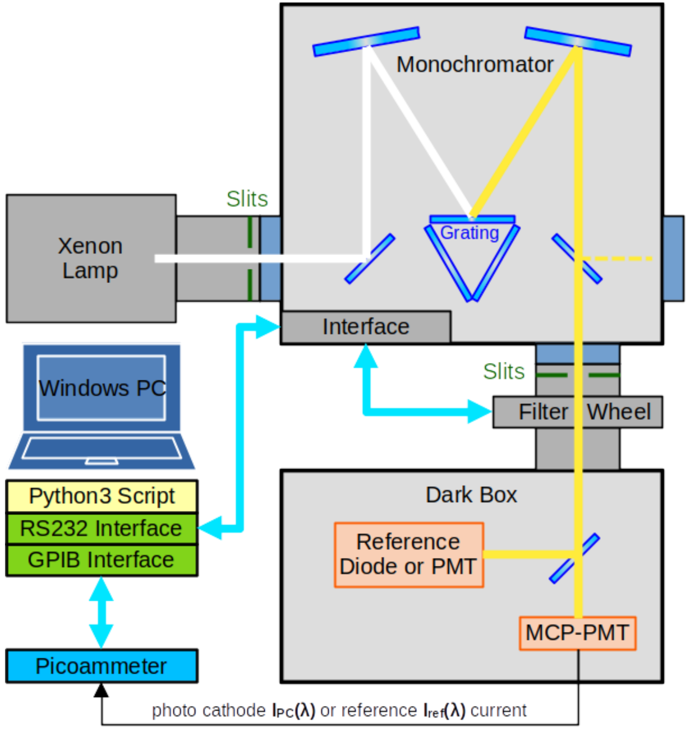


Photek MAPMT253

- **rather new development !**
- 1-layer ALD coating; no film
- available as 8x8 to 64x64 anode array
- customer configurable anode readout and interconnect
- active / total size: 53x53 / 61x62 mm^2
- **active area ratio: 74%**
- pore size: **15 µm** and **6 µm**
- **CE ≥ 80%**
- ongoing performance improvements

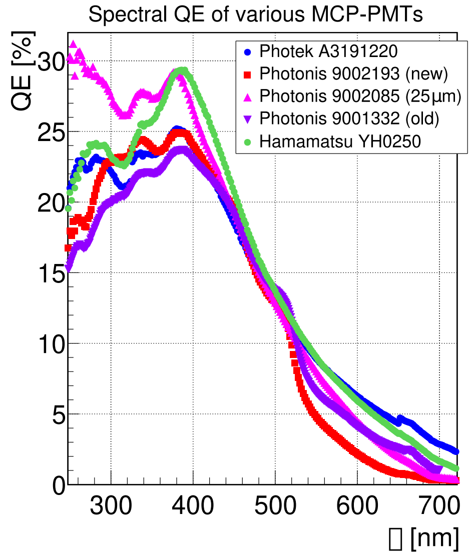


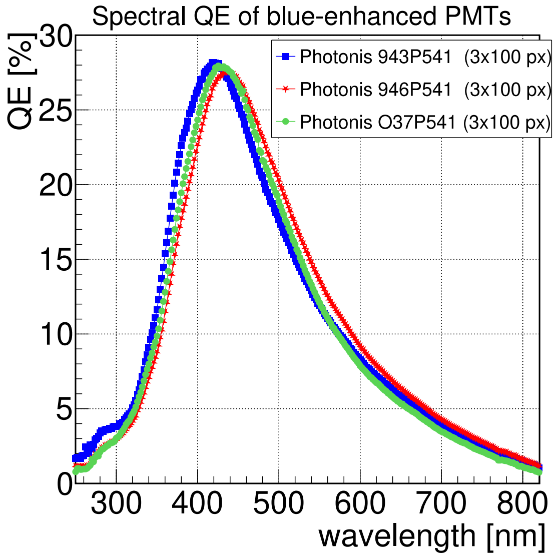
Spectral QE



$$QE_{PC}(\lambda) = QE_{ref}(\lambda) \cdot \frac{I_{PC}(\lambda) - I_{dark,PMT}}{I_{ref}(\lambda)}$$

- QE(λ) setup
  - Monochromator LOT Oriel MSH301 (later named Oriel Cornerstone 260)
  - <1 nm resolution from 200 to 800 nm
  - Hamamatsu S6337 reference diode
  - Keithley 487 picoammeter
  - ~5 mm light spot at PC (no saturation)
  - Measure $I_{PC}(\lambda)$ (few nA) directly at PC with 200 V between PC and MCP-in
- QE results
  - QE of older MCP-PMTs around 20%
  - Latest PMTs with peak QE up to 30%
    - Hamamatsu, Photonis, and Photek
    - Some enhanced in UV region
  - QE of latest Photonis PMTs can be tailored to customer needs
    - Narrow bands around blue, green, red available



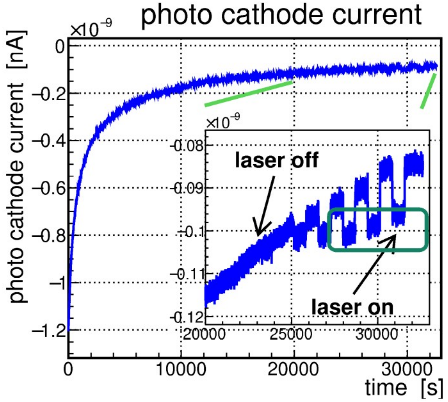


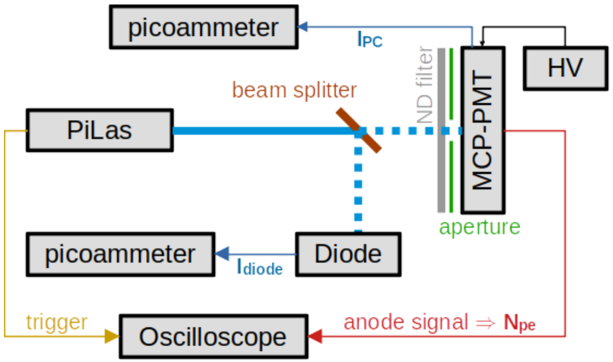
Collection Efficiency (CE)

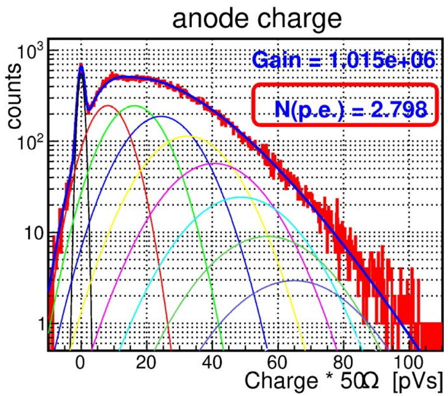
$$CE = \frac{N_{pe@anode}}{N_{pe@PC}} = \frac{N_{pe@anode@LR} \cdot e \cdot LR}{I_{PC@HR}} \cdot \frac{I_{diode@HR}}{I_{diode@LR}}$$

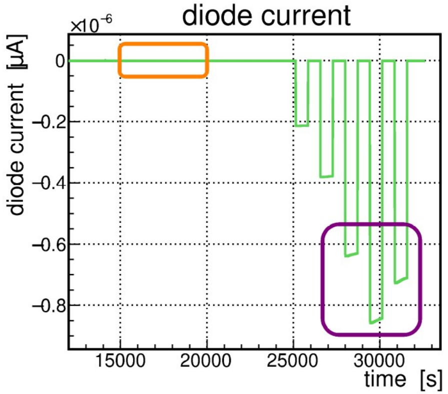
with

$N_{pe@anode}$ = p.e. at anode
$N_{pe@PC}$ = p.e. at photocathode PC
$N_{pe@anode@LR}$ = low rate anode p.e.
$I_{PC@LR}$ = low rate current at PC
$I_{diode@HR}$ = high rate diode current
$I_{diode@LR}$ = low rate diode current
e = elementary charge
LR = low rate



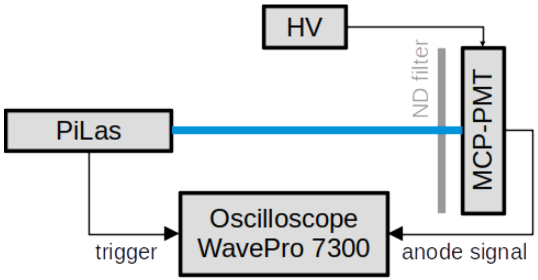






- CE measurement is easy in principle, but very low currents (~10 pA @30 MHz [~2 p.e.]) at PC
  - $N_{pe@anode}$ from pulse height spectrum
  - $N_{pe@PC}$ from PC current scaled by diode current ratio
- Final result is taken as the mean of several intensity and frequency configurations
- **Most recent MCP-PMTs with ~85 – 95% CE**
- CE depends on HV between PC and MCP-in

Gain

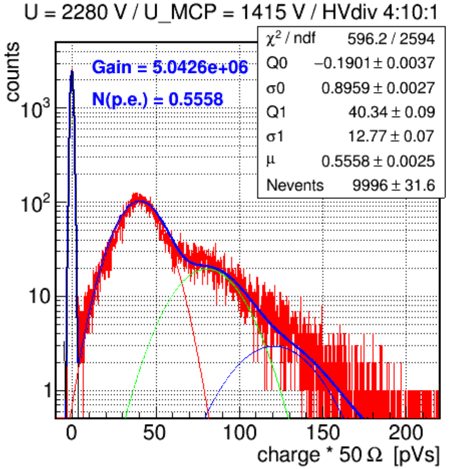


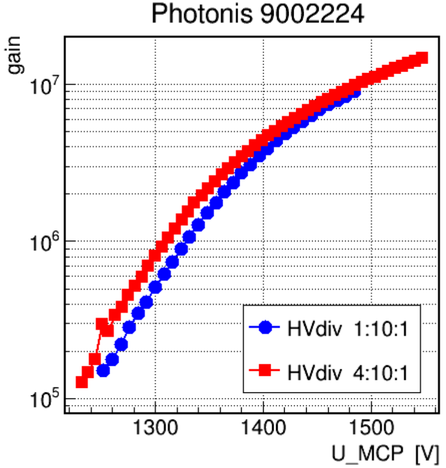
Only 1 pixel illuminated

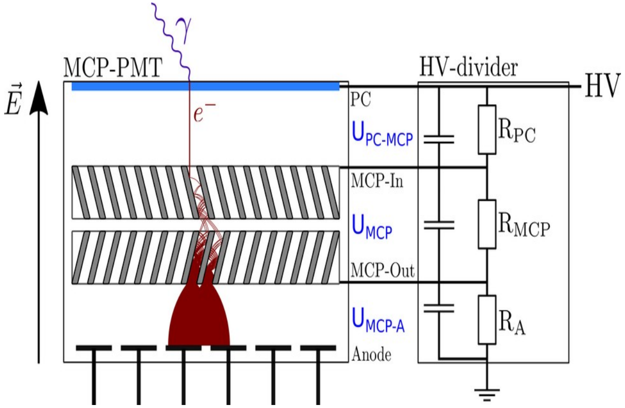
$$Q_n = Q_0 + nQ_1$$

$$\sigma_n = \sqrt{\sigma_0^2 + n\sigma_1^2}$$

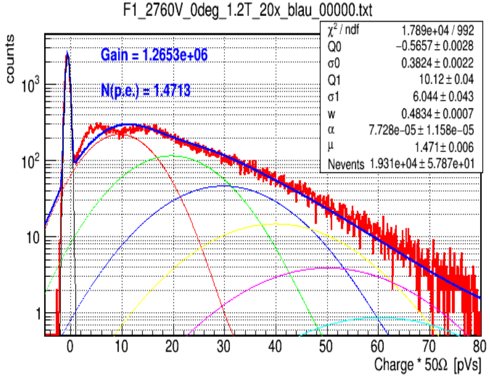
$$S_{MCP}(x) = \sum_{n=0}^{24} \left\{ \frac{\mu^n \cdot e^{-\mu}}{n!} \cdot \frac{1}{\sigma_n \sqrt{2\pi}} \cdot \exp\left[-\frac{(x - Q_n)^2}{2\sigma_n^2} \right] \right\}$$

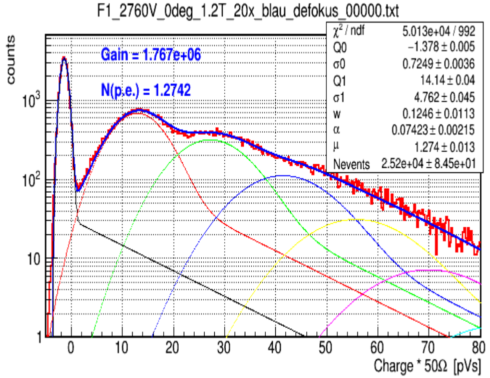






Photek MAPMT253 [A1200116]



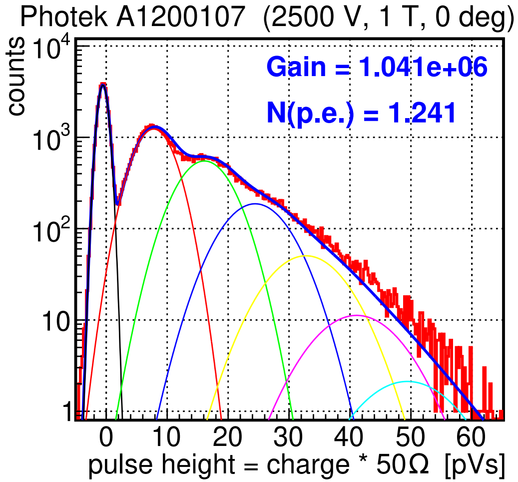


- **Important**
  - Moderate photon rate (kHz) per area to avoid saturation
  - Saturation causes distorted pulse height distributions
- **Gain**
  - Good P/V in single photon pulse height spectra at ~10^6
  - Voltage from <2.0 to 2.8 kV for 10^6 gain
  - Photonis PMTs operated at various voltage divider ratios ($R_{PC}:R_{MCP}:R_A$ = 4:10:1 to 2:10:1 instead of standard 1:10:1) → **improves RMS time resolution**

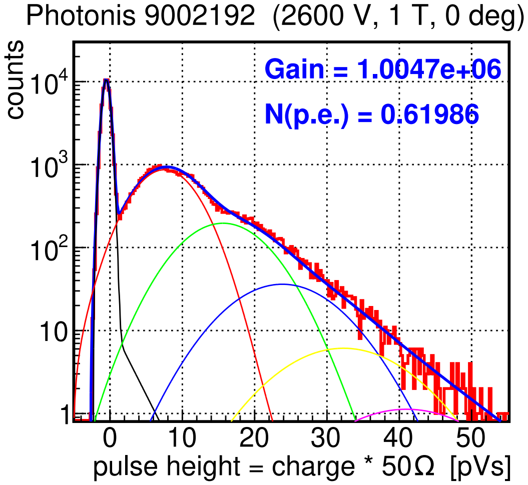
Gain in B-Field

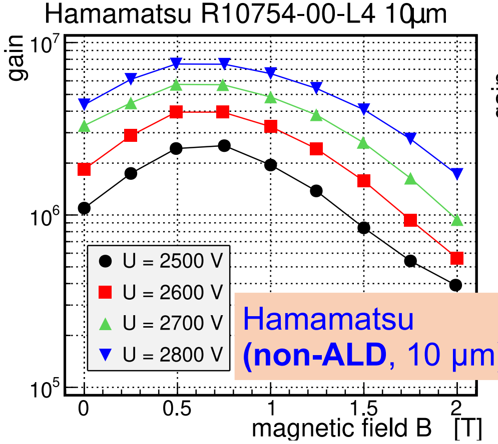
- ALD PMTs much more sensitive to B-field
  - **non-ALD:** Gain ratio 0T/1T ≤ 1
  - **ALD:** Gain ratio 0T/1T ≈ 3 for 6 µm and 10 µm
- Still very good P/V ratio at 1 T
- Gain ratio between 1T and 2T
  - 2 – 5 for 6 µm dependent on tilt angle
  - 10 – 20 for 10 µm dependent on tilt angle
- Photonis 3x100 less sensitive than 8x8

Photek (8x8, ALD, **6 µm**)

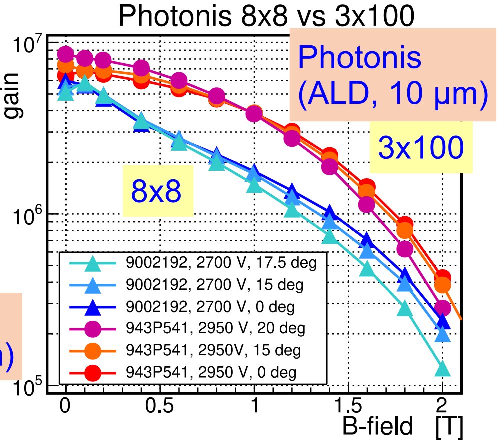


Photonis (8x8, ALD, 10 µm)

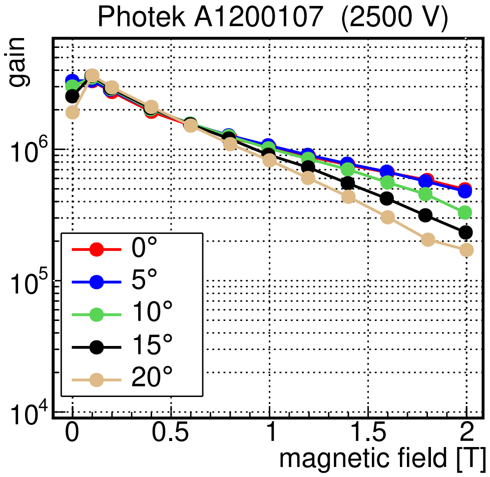


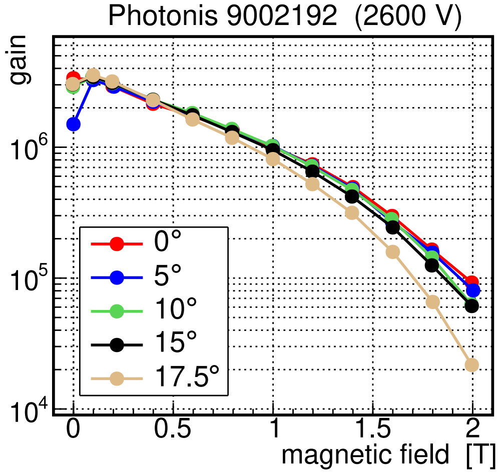


Hamamatsu (**non-ALD**, 10 µm)

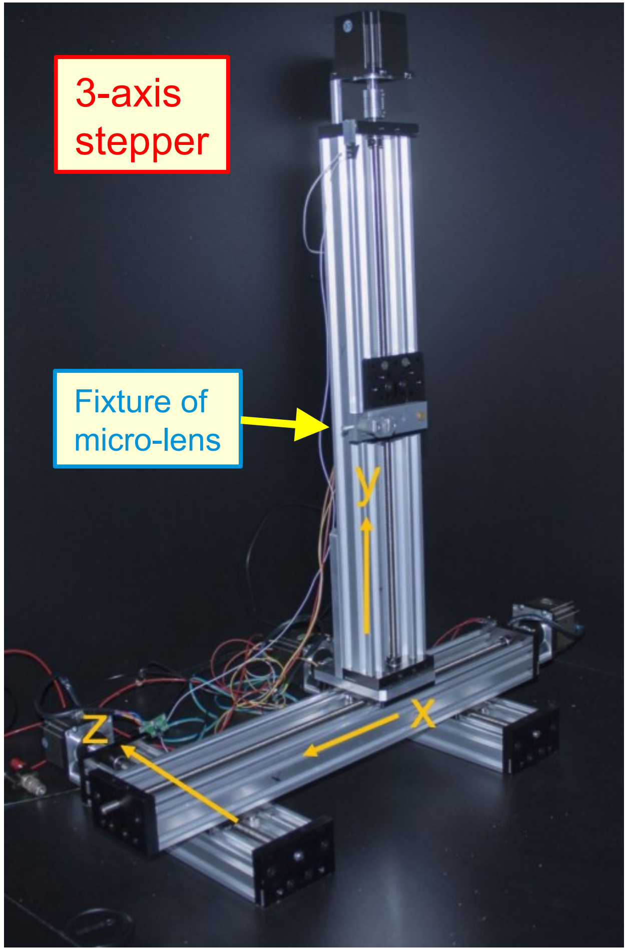


Photonis (ALD, 10 µm)





3-axis Stepper for Automated xy-Scans



- Self-built 3-axis stepper
  - ~40 cm in x- and y-direction; ~15 cm in z-direction
    → scan of four (or more) 2-inch MCP-PMTs simultaneously
  - "C-Beam" profiles linear guidance system (extruded aluminum)
  - Step motors controlled by TMC2130 Trimanic step motor drivers
    - sensor-less engine load detection which notices when stepper runs against boundaries or other parts
    - Steering done by "Teensy 3.5" microcontrollers programmed in an Arduino development environment
    - Theoretically possible: distance of 2.5 μm per step
    - Reachable true positioning accuracy ≤10 μm (tested with CCDs)
  - Micro-focus lens system attached to 3-axis stepper
    - Focus can be adjusted by moving the lens position along z
    - Light spots down to <50 μm peak width possible (aperture needed)
    - **Lens usually not fully focused to avoid charge saturation effects**
  - Mono-mode optical fiber between PiLas laser head and lens system
  - Typical photon rates of 1 – 100 kHz per measurement point

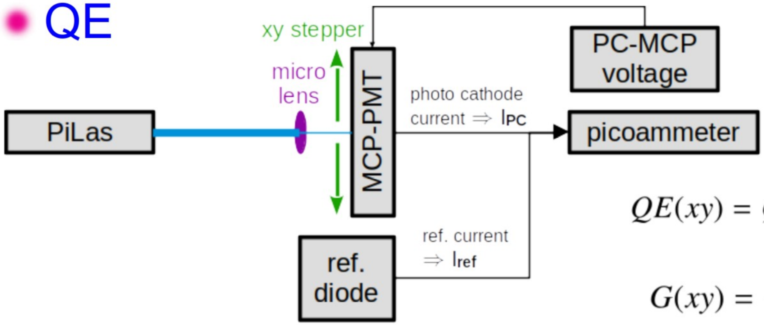
QE and Gain Homogeneity

Apply moderate focus → avoid saturation of currents in both QE and gain scans!

Standard step size: 0.025 - **0.5 - 1** mm

Measured at one laser wavelength λ_{scan} = 372 nm

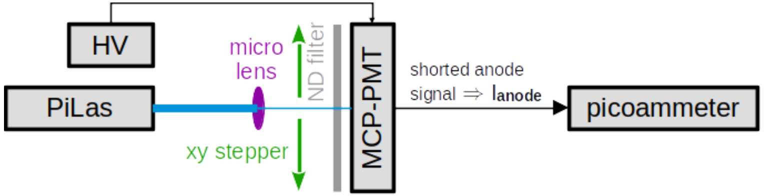
- QE

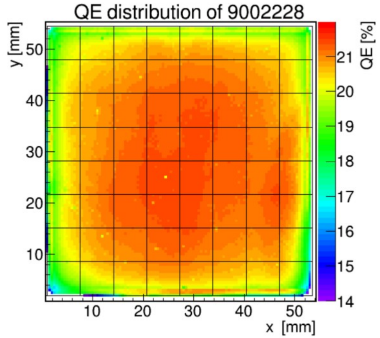


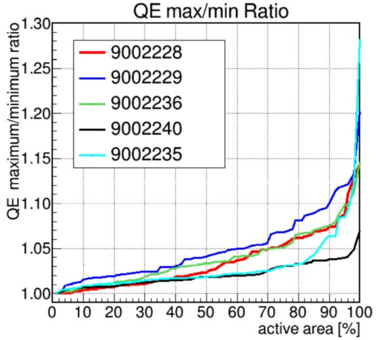
$$QE(xy) = QE_{ref}(\lambda_{scan}) \cdot \frac{I_{PC}(xy) - I_{dark,PMT}}{I_{ref}}$$

$$G(xy) = \frac{I_A(xy) - I_{dark}}{I_{A,refpix} - I_{dark}} \cdot G_{refpix} \;/\; QE(xy)$$

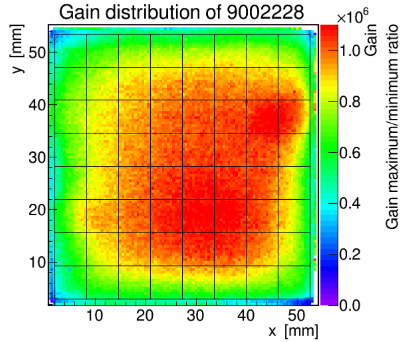
- Gain

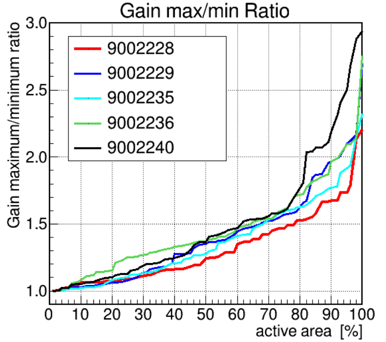






max/min ratio per pixel:
(mean of all measured xy positions at max. pixel) / (mean of all measured xy positions at other pixels)

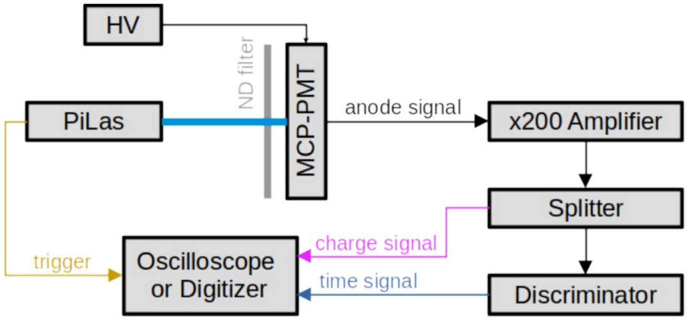


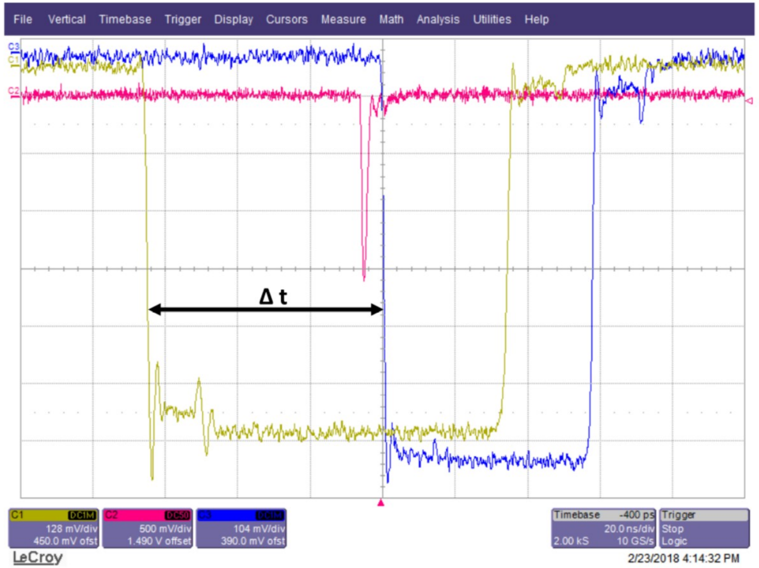


- ~300k p.e. (ND0) @ 100 kHz → I_{PC} ~ 5 nA
- generally good homogeneity
- QE max/min ratio <1.2 for >>90% of active area
- worse at rims and corners

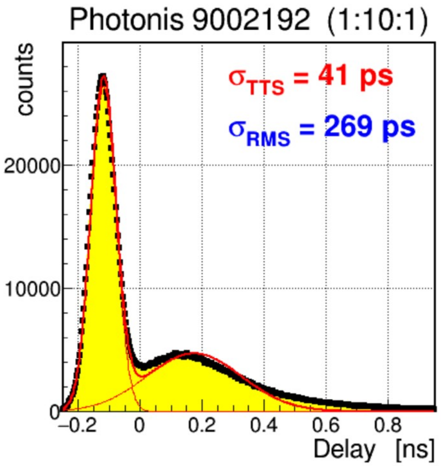
- ~1 p.e. @ 50 kHz @ 10^6 gain → I_{anode} ~ 8 nA
- moderate homogeneity (QE corrected)
- gain max/min ratio <3 for 90% of active area
- lower gain always at rims and corners

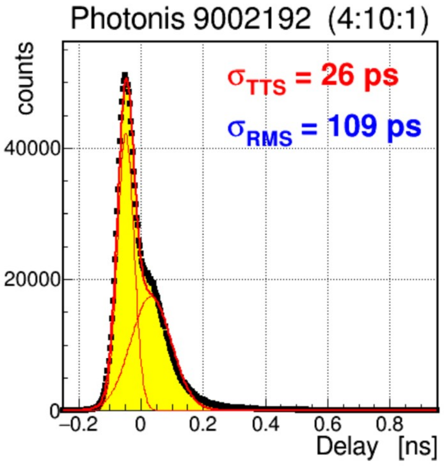
Time Resolution



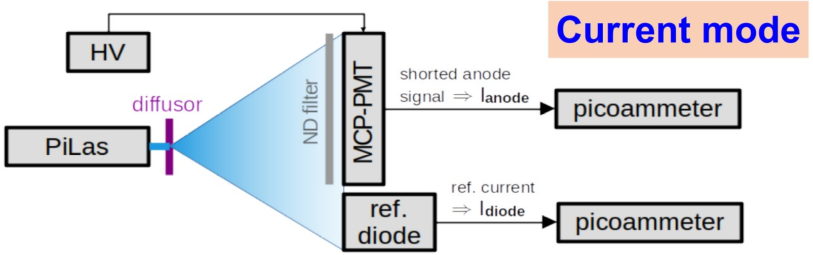


- Time resolution measurements
  - Usually done with LeCroy WavePro 7300A scope
  - Sometimes with CAEN DT5742B digitizer
  - Photon intensity at **single photon level and low rate**
- Jitter between Pilas trigger and anode signal
  - Anode charge + time delay: timewalk correction
- Different voltage divider configurations
  - R_{PC}:R_{MCP}:R_A = 1:10:1 → rather poor RMS resolution
  - 4:10:1 → much better time resolution (and good CE)

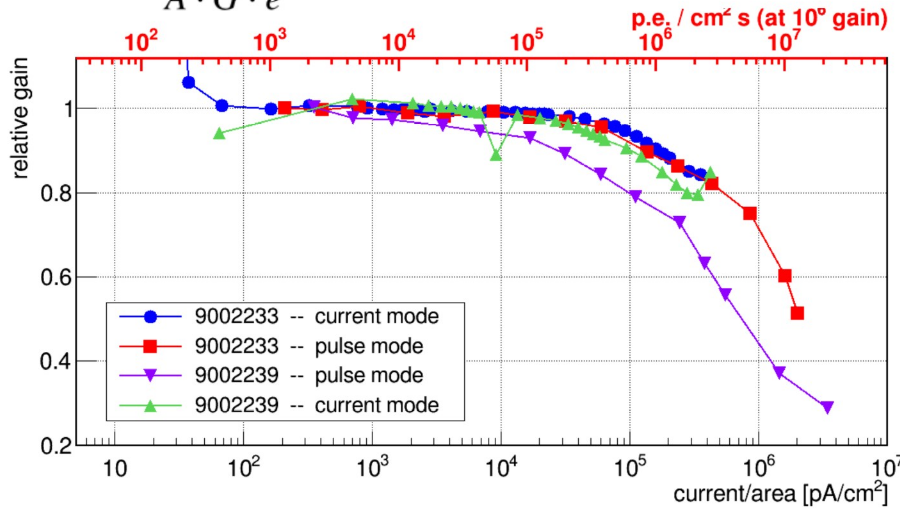




Rate Capability



$$R = \frac{I_{anode}}{A \cdot G \cdot e}$$



- Anode current measurement (“current mode”)
  - **Homogeneous illumination of full active surface** for different laser frequencies f and light intensities
  - All anode pixels shorted → measure anode current

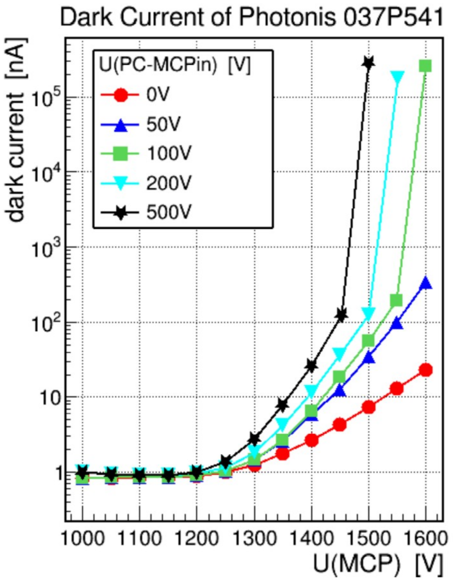
$$G_{rel} = \frac{I_{anode@f} - I_{anode,dark}}{I_{anode@f_{ref}} - I_{anode,dark}} \cdot \frac{I_{diode@f_{ref}} - I_{diode,dark}}{I_{diode@f} - I_{diode,dark}}$$

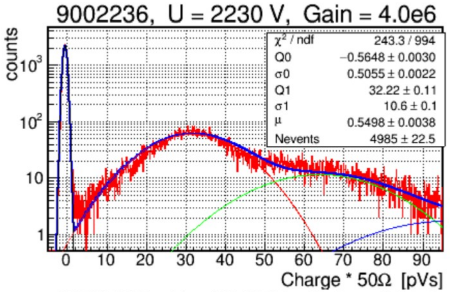
  - Situation is similar to what is expected in reality
- Pulse height measurement (“pulse mode”)
  - **Illumination of one anode pixel** with different laser frequencies and intensities
  - Measure the pulse height distribution with an oscilloscope and unfold it with a fit → N_{pe} and gain G

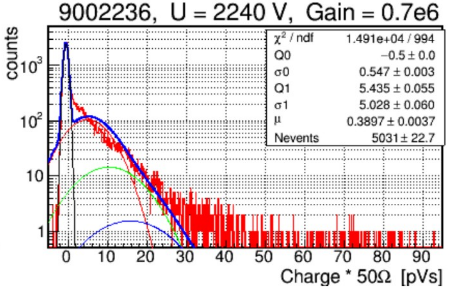
$$\frac{I_{anode}}{A} = \frac{f \cdot e \cdot G \cdot N_{pe}}{A}$$

  - Usable to study rate dependence at different positions
- Results
  - Ideally same rate dependency for both modes
  - Sometimes they show different slopes (R uniformity?)

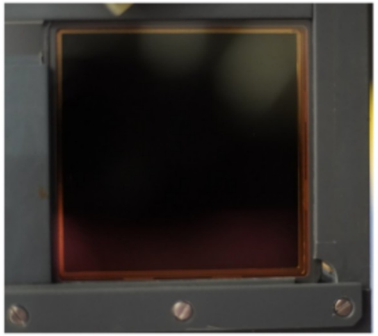
"Escalation"

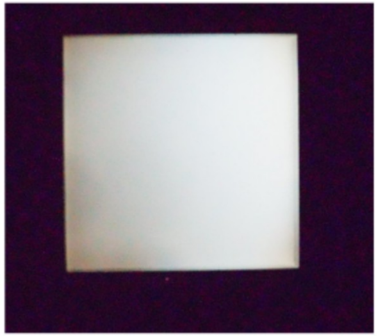






Photonis 9002193

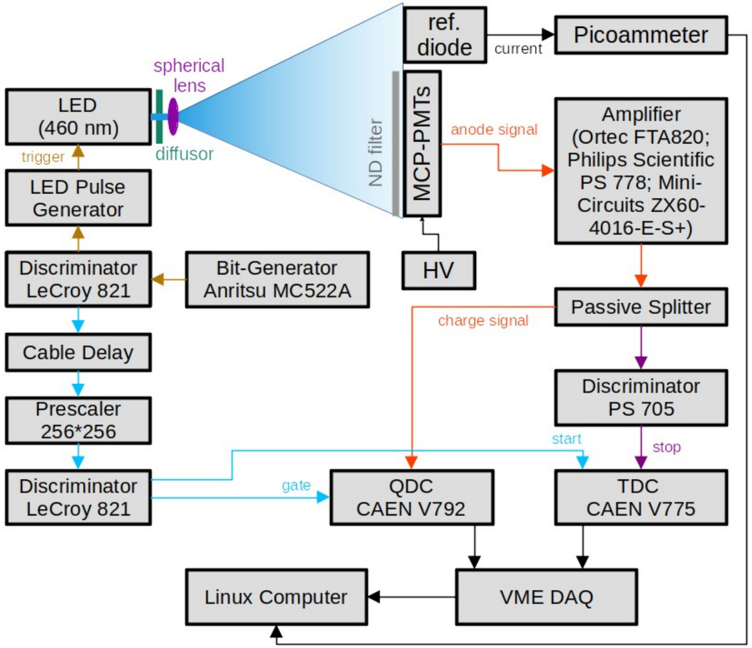


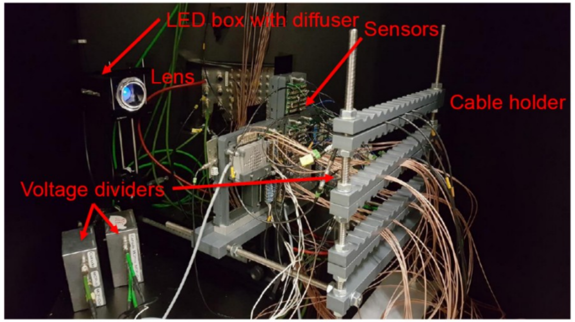


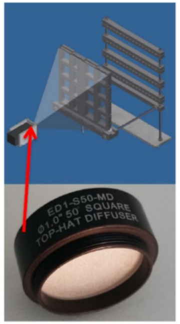
- New "escalation" effect seen in MCP-PMTs
  - **MCP-PMT behavior may change suddenly** (voltage change of ~10 V can be enough)
  - Dependent on photon intensity and high gain (at high gain even darkcounts may trigger the effect)
  - Effect was never seen with 1-layer ALD tubes
  - Until now only observed in Photonis MCP-PMTs with 2 ALD layers (what about LAPPD and HRPPD?)
- Signatures
  - Massive count rate (dark current) increase of several orders of magnitude
  - Significant gain drop (saturation)
  - Drop of the MCP resistance
  - Significant production of photons with white spectrum
  - The whole effect seems **suppressed already in moderate B-fields**
- Likely Explanation
  - Photons are generated in ALD layer and/or electrode
  - Many escalation photons trigger a recoupling in PC

Measurement of MCP-PMT Lifetime

- Continuous illumination
  - LED pulse generator (~5 ns, 70 V) triggers a 460 nm LED at ~1 MHz rate (comparable to PANDA DIRCs)
  - In front of MCP-PMT attenuated to **single photon level**
  - All MCP-PMTs share same light spot (~30x30 cm^2) [quite homogeneous by using a thick lens and a Thorlabs ED1-S50-MD rectangular diffuser]
- CAEN VME DAQ
  - Permanent recording of MCP pulse height (at a highly prescaled rate) → integrated anode charge (IAC)
  - Determine gain + DCR before and after QE measurement
- Q.E. measurements
  - Same setups as in normal QE scans (λ and xy-position)
  - Every 4-6 weeks: wavelength scan
  - Every 3-4 months: complete surface scan at 372 nm

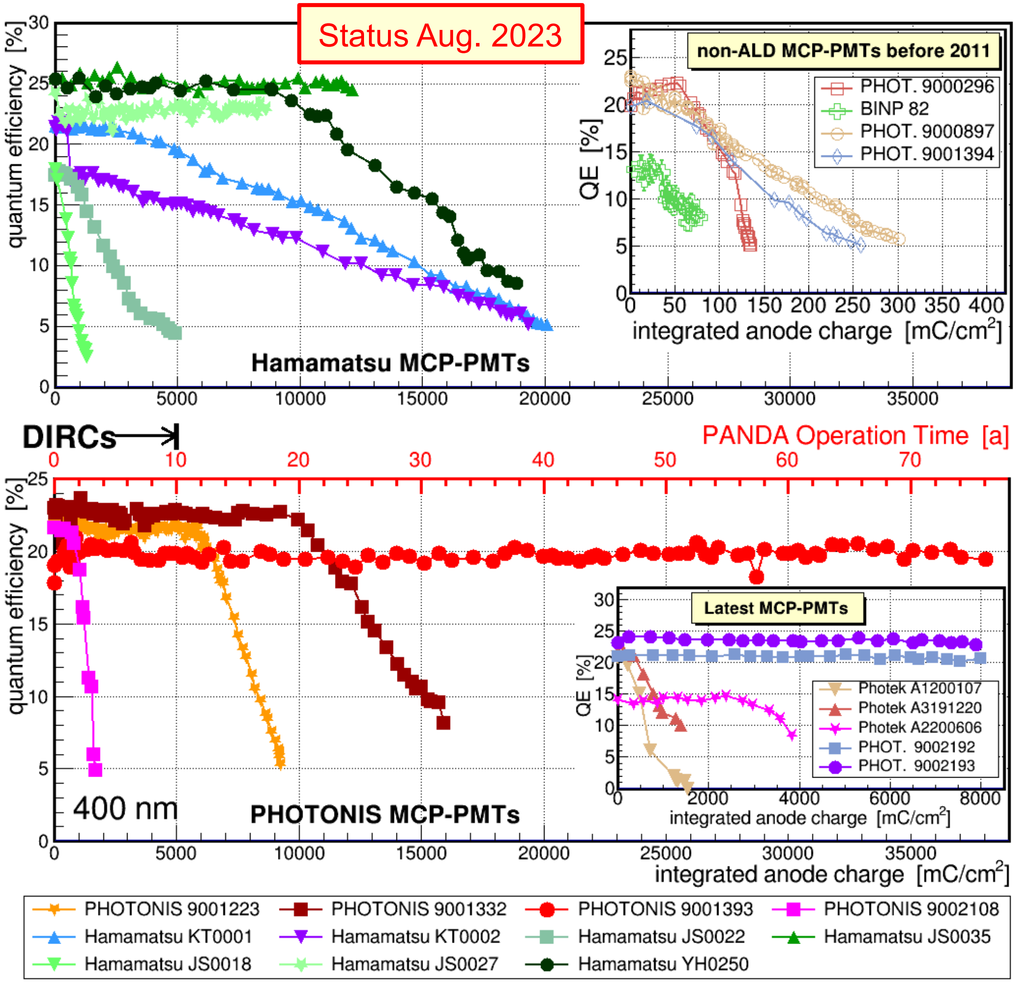






Simultaneous illumination of up to 16 2-inch MCP-PMTs possible

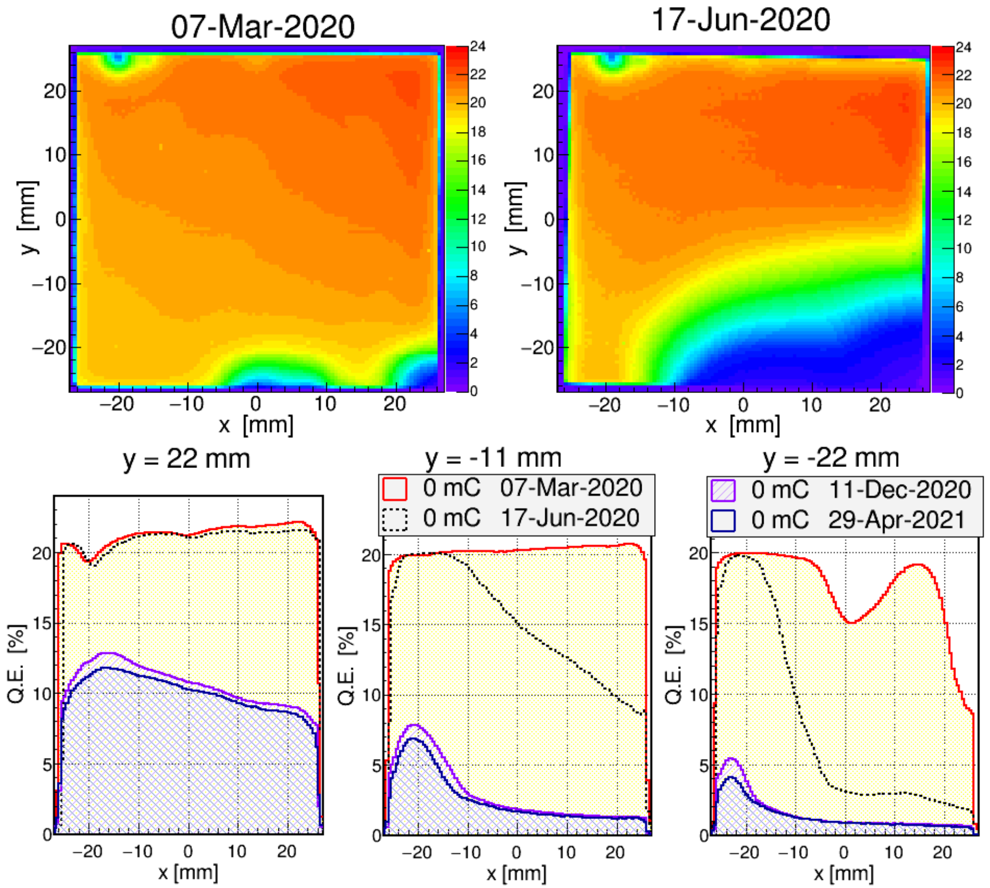
Results with ALD-coated MCP-PMTs



- Expected integrated anode charge (IAC) in 10 years PANDA: (at 50% duty-cycle, 20 MHz anti-proton-proton average annihilation rate, 10^6 sensor gain)
  - **~5 C/cm² for PANDA Barrel DIRC and even more for Endcap Disc DIRC**
  - Older MCP-PMTs had >50% QE loss after <200 mC/cm² IAC → few months lifetime
  - Aging problem solved by coating the MCP pores with an atomic layer deposition **(ALD)** technique
- IAC >5 C/cm² for most ALD MCP-PMTs
  - Confirmed by other measurements
- Lifetime of best MCP-PMTs with ALD coating
  - **38 C/cm²** for Photonis 9001393 with 2 ALD layers
  - **Increase by factor ~200 compared to 2011 !**
  - Latest Photonis (2 ALD layers) at ~8 C/cm²
  - Photek A2200606 (1 ALD) at ~4 C/cm² → **QE loss**

Signature of Vacuum Microleaks

Photek MAPMT253 [A1200116] (8x8, ALD, 6 µm)

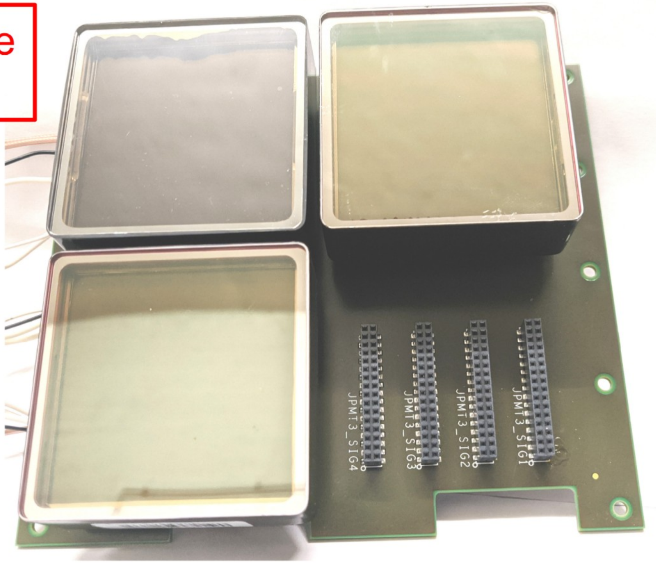


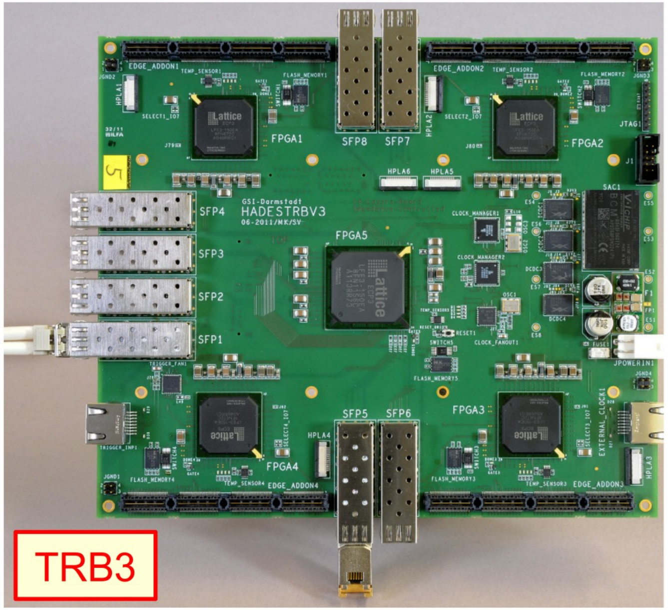
- QE xy-scans same as in homogeneity tests
- Within typically months the tubes loose QE starting somewhere at a corner or the rim
  - Already after PMT delivery a lower QE is visible in one of more small spots
  - QE loss starts growing from these spots
  - Finally spreads across whole PC
  - Obviously QE does not vanish completely
- Examples of PC aging without illumination:
  - Some of the first Hamamatsu 2-inch MCP-PMTs
  - The first Photek 2-inch tubes we received
  - Two of the most recent Photonis MCP-PMTs (reason was a broken brazing furnace)
- A bit worrisome: we have observed this in one tube that was good for ~2 years
  - after B-field tests: caused by handling or B-forces?

DiRICH/TRB3 DAQ

- FPGA based DAQ: TRB3, DiRICH, 4 PMTs/backplane
  - Developed at GSI for HADES and CBM
  - **32 chan. DiRICH FEE boards**: amplification, discrimination, TDC, ToT
  - **256 chan. TRB3**: distribution of trigger signals and accumulation of data
  - Power supply and data concentrator card at each backplane
  - < 20 ps RMS; 700 kHz max. trigger rate

backplane frontside

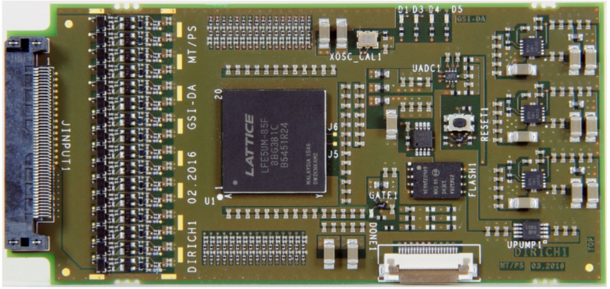




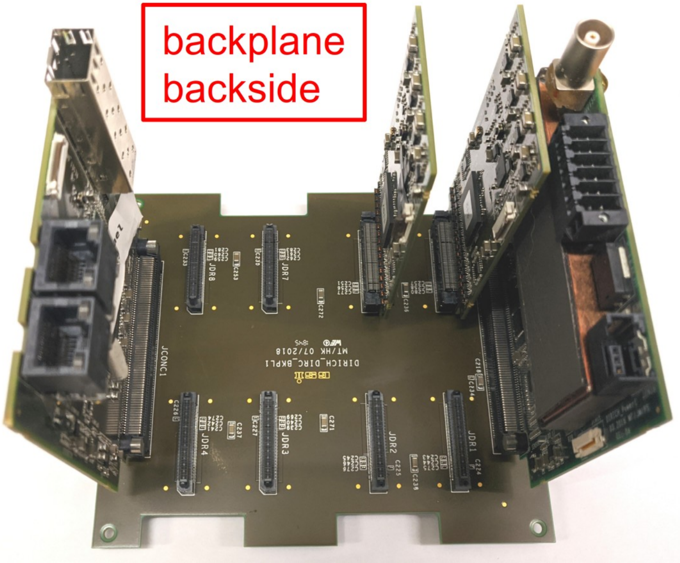
TRB3

DiRICH/TRB3 DAQ-system:
A.Neiser et al., JINST 8 (2013) C12043
C. Ugur et al., JINST 11 (2016) C01046
J. Michel et al., JINST 12 (2017) C01072
A. Rost et al., JINST 12 (2017) C02047
The TRB3 website: http://trb.gsi.de

DiRICH

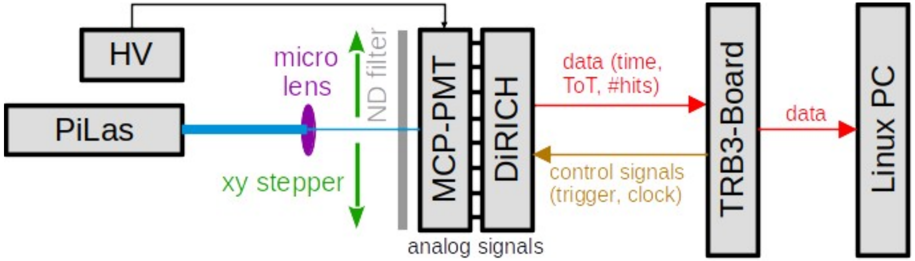


backplane backside

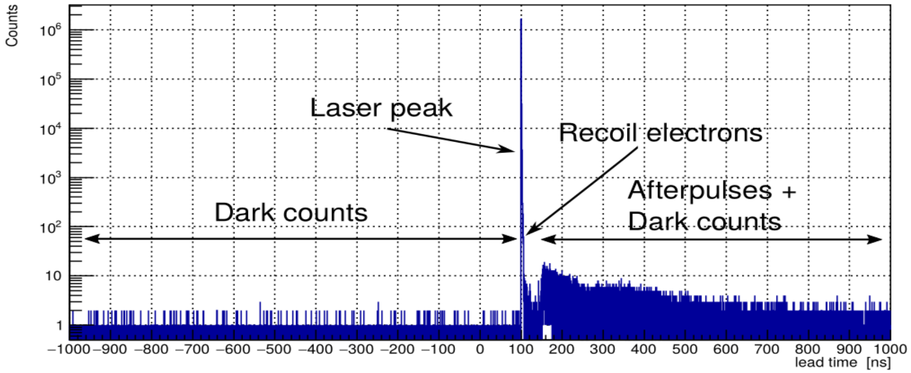


PMT Quality Control Scans with DiRICH/TRB3

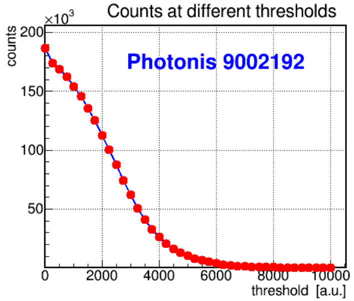
- **Automated quality control measurements for series production Barrel DIRC MCP-PMTs**

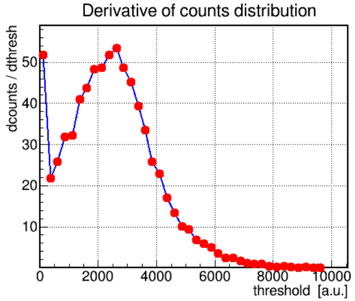


- Measure **time delay** between laser pulse and pixel response
- For easier analysis laser peak shifted to 100 ns for all channels

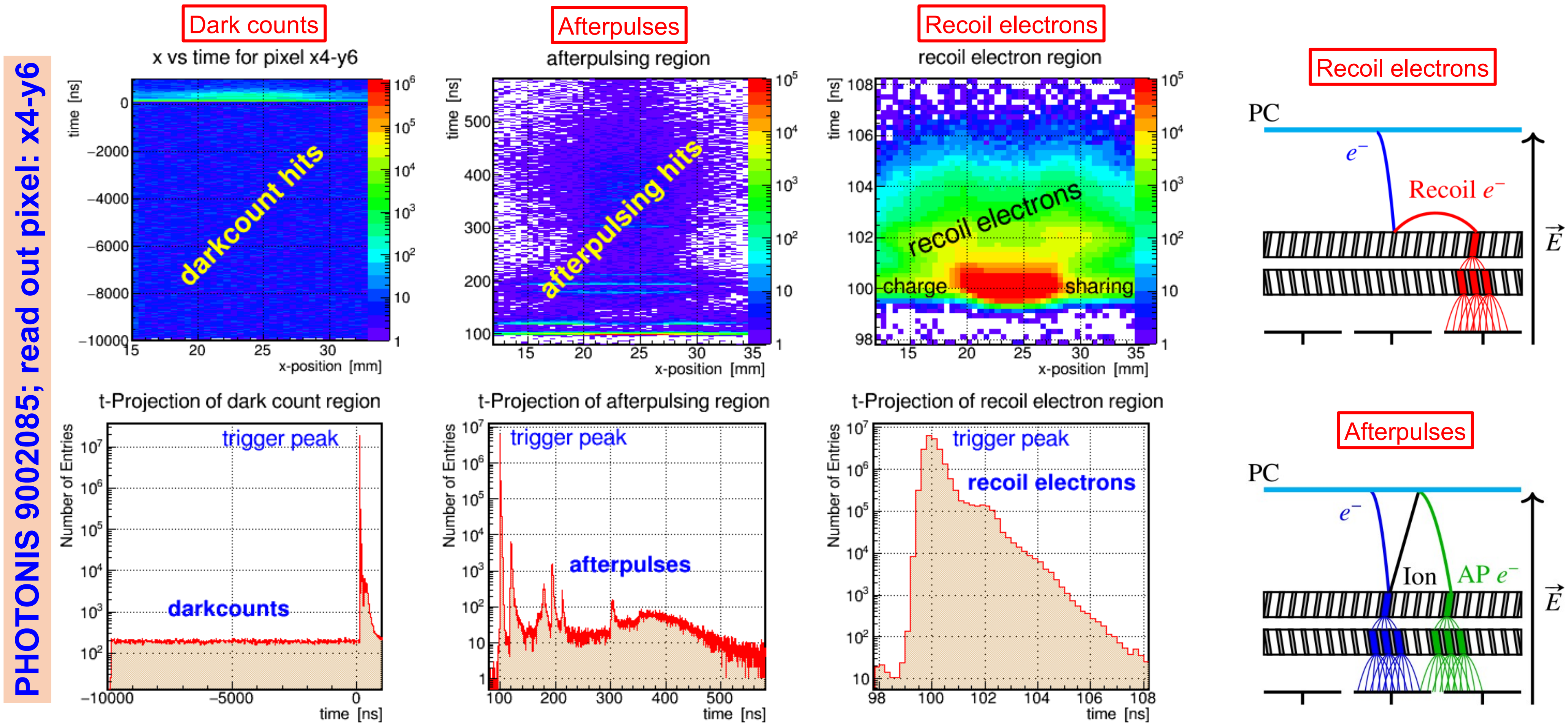


- <u>Each channel:</u> permanently recording time and time-over-threshold (ToT) information of all hits above a freely selectable threshold
- Record all hits for each pixel within a certain time window (e.g., -10 to +1 μs) around PiLas trigger
- xy-scans (½ – 1 mm steps): information per channel
  - x-, y-position, hit time, ToT, number of hits
  - **Time resolution** (TTS and RMS) per anode pixel
- 3D-info (x,y,t) allows access to higher level information
  - **Darkcount** xy-distributions
  - Charge sharing (and electronic) **crosstalk** behavior
  - **Recoil electron** distributions (position and time)
  - **Afterpulse** distributions → TOF of feedback ions
- Threshold scan
  - Count hits
  - Derivative yields pulse height distribution per anode pixel





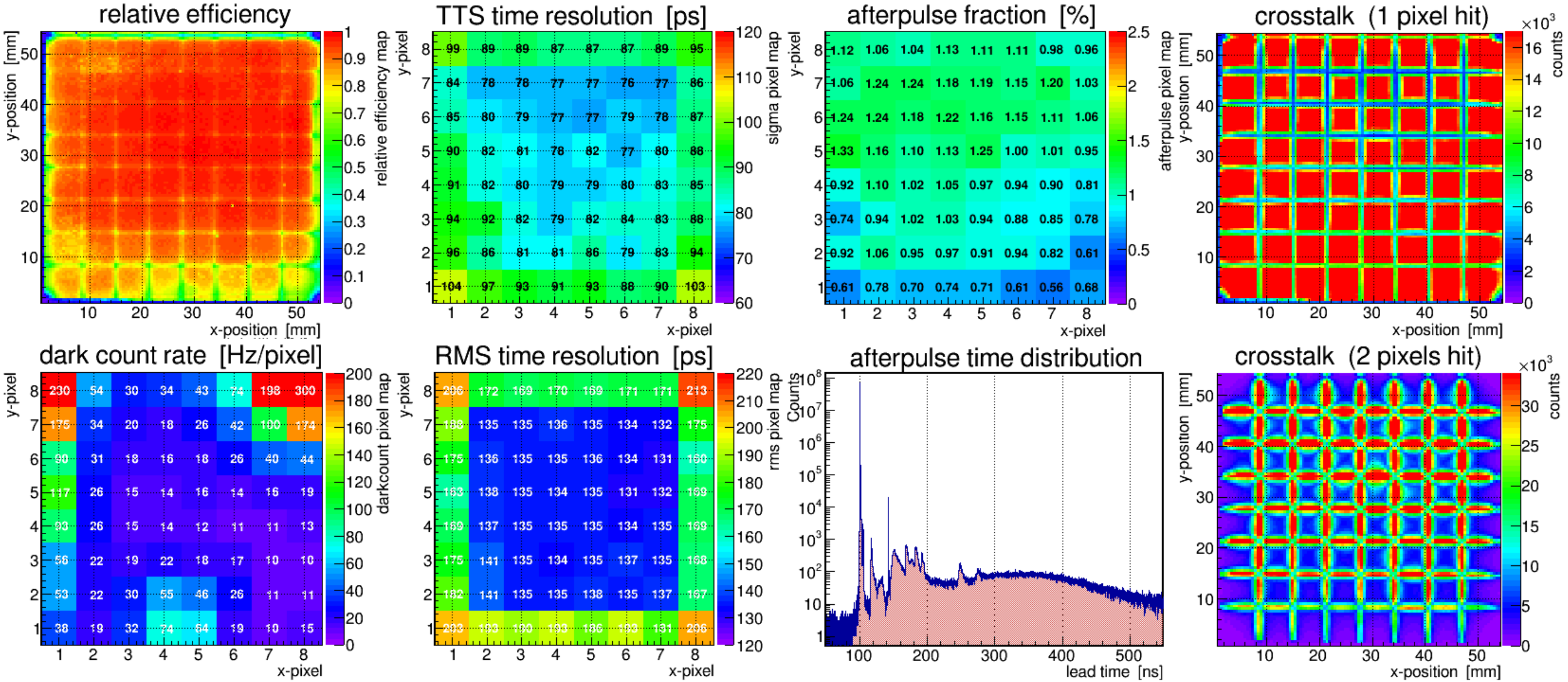
Information from DiRICH/TRB3 Scans



Example Results of xy-Scans with DiRICH/TRB

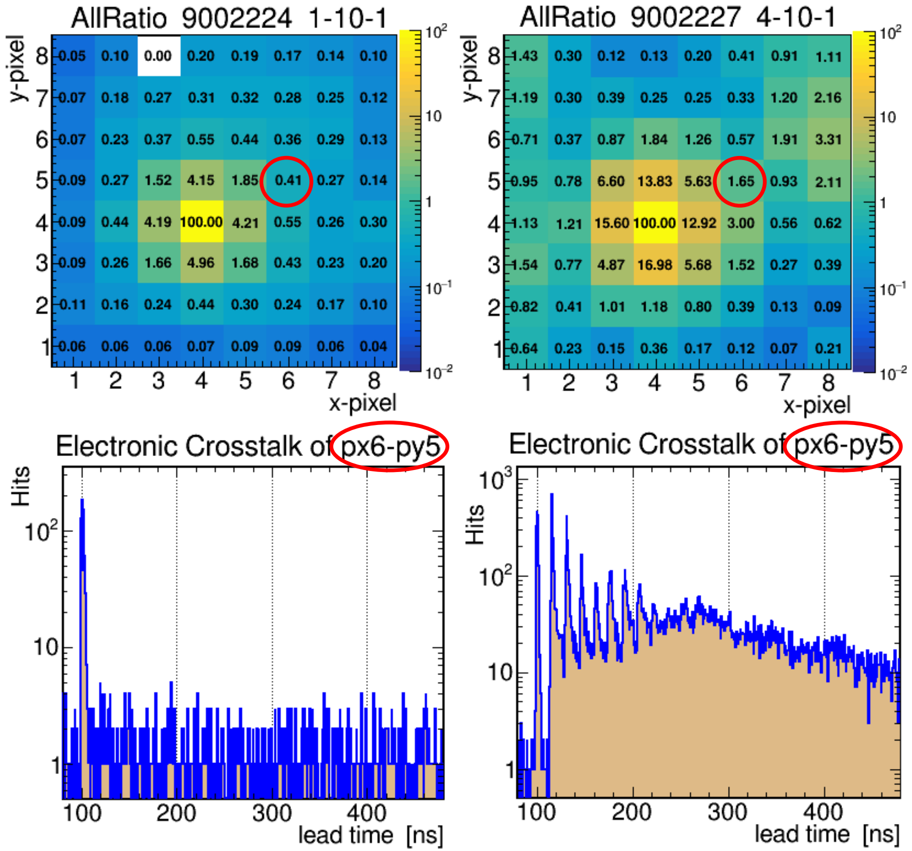
!! All results obtained with **one single xy-scan** of ~21 hours (½ mm steps; 13689 measured positions) !!

PHOTONIS 9002229



Determination of Electronic Crosstalk

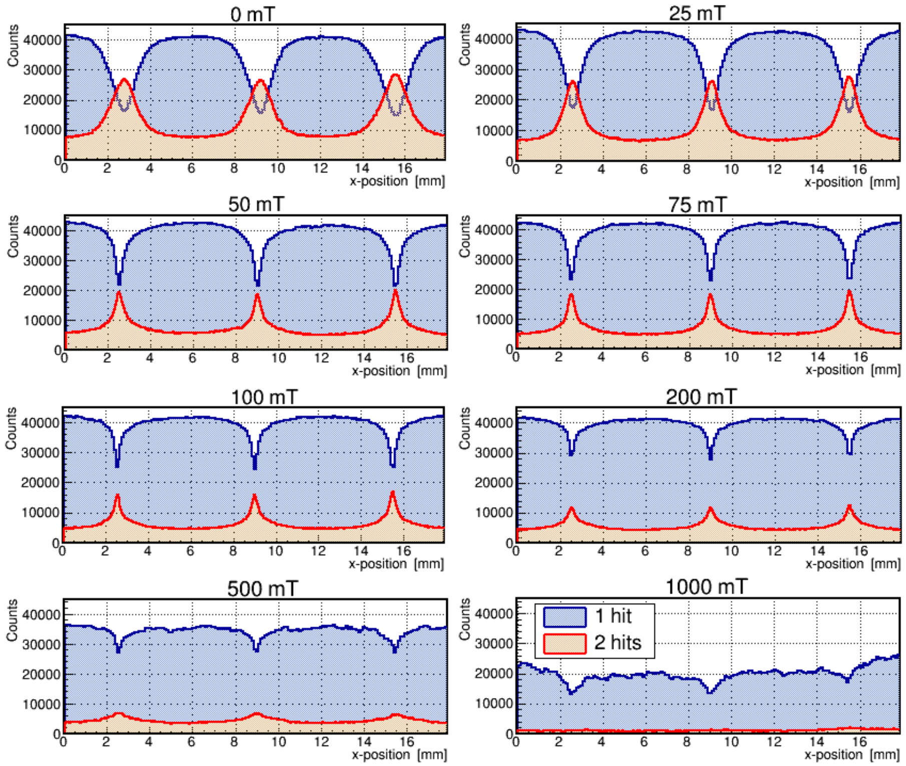
Only one pixel (x4-y4) illuminated



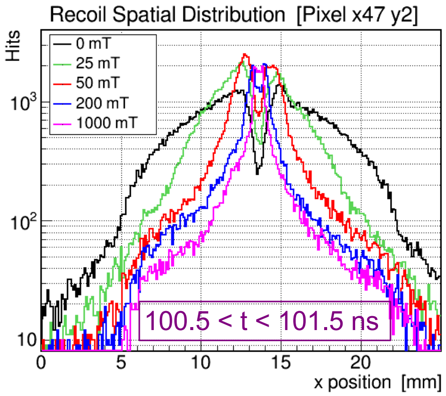
- TRB position scans may be used to quantify electronic cross talk
  - Take data where only one pixel was illuminated (here 2.5x2.5 mm^2 of pixel x4-y4)
  - Determine fraction of detected hits (dark count corrected) in every pixel normalized to x4-y4
  - Adjacent pixels to x4-y4 are also populated with recoil and afterpulse hits
  - After DCR correction pixels in second (and further) rows should contain mainly electronic crosstalk hits
- Crosstalk maps and time distributions
  - Electronic crosstalk across the whole active PMT area is typically ~1% or lower
  - Depends on MCP-PMT and HV divider configuration
  - Analyzes show that afterpulse hits (high amplitude) create much more electronic crosstalk
  - Time distributions may show “funny” structures

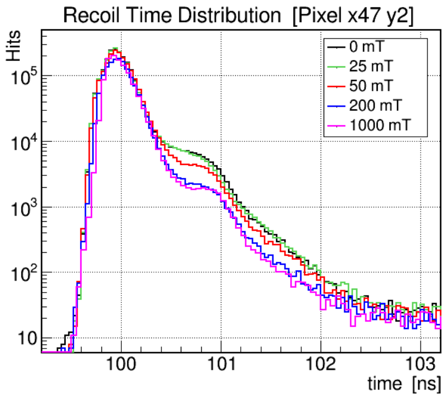
Electron Focusing inside Magnetic Fields

Photonis 9002224 (8x8 px): x-scan (50 μm steps) of 4 pix read out by TRB DAQ → less **charge sharing crosstalk**



Photonis 946P541 (100x3 px): x-scan (25 μm steps) to test space and time distributions of **recoil hits** with TRB DAQ





- Crosstalk between anode pixels
  - Better defined pixel position already at B = 0.1 T
  - Fewer charge sharing crosstalk (electrons focused)
- Distribution of recoil electrons
  - Spatial spread shrinks with increasing B-field
  - Slope of time distribution unaffected

Comparison of Photek and Photonis PMTs

Performances from evaluation of 2-inch MCP-PMTs for PANDA Barrel DIRC

Performance Parameter	Barrel DIRC Requirement	Performance Values: Photek A1200107	Photek A3191220	Photonis 9002192	Photonis 9002193
Active area ratio (%)	>72	74.1	74	76.6	79.8
Useful area (cm^2)	2"x2" = 25.8	28.1	27.6	26.5	27.6
Number of pixels	64 (8x8)	OK	OK	OK	OK
Outer dimension	58 mm x 58 mm to 62 mm x 62 mm	61.4x61.9	60.3x61.8	58.8x58.8	58.8x58.8
Front window material	sapphire or fused silica	OK	OK	OK	OK
Spectral range	QE (%) at 290 nm	>20	>20	>20	>20
Darkcount rate (Hz/cm^2)	< 1000	263	69	24	183
TTS (ps)	<= 50	40	36	26	27
RMS timing precision (ps)	150-200 ps or better in [-0.5…+2] ns time window around main peak at standard operating voltage (less than 3.0 kV at B = 0 T)	**215**	199	109	109
Afterpulse fraction (%)	< 2% @10^6 gain	0.14	0.49	1.74	0.79
10^6 Gain at voltage (V) with standard divider	at least 10^6 @ standard operating voltage (less than 3.0 kV at B = 0 T)	2400	2300	1960	1880
Rate capability (current; pulse mode)	10% max gain loss at 0.5 MHz/cm^2@10^6 gain	1; **0.8**	1; 0.95	0.92; 0.95	0.93; 0.95
Pulse height distribution (P/V)	typical P/V > 3 measured on the total area @10^6 gain (0 T; 1 T)	**2.7**; 7.1	**2.2**; 6	**2.6**; 3.6	3.2; 2.8
Peak quantum efficiency (QE) at 300-400 nm	>= 18%	24.4	25.0	22.2	24.7
Collection efficiency (CE)	>= 65%	95	72	76	75
Detective quantum efficiency DQE = CE*QE	>= 12%	23.2	17.9	16.8	18.5
Gain uniformity across active area	max/min ratio 3 or better	**7.7**	**12.5**	**4.2**	**3.1**
QE uniformity at peak wavelength	max/min ratio <1.15 in central sensor region (inner 2x2 pixels), <3 elsewhere	1.02; 1.92	1.04; **8.33**	1.0; 1.28	1.01; 1.35
High magnetic field compatibility	≤10 µm pores MCPs	6	6	10	10
Lifetime (QE drop)	<5% QE drop at 2 C/cm^2 and <10% QE drop after 5 C/cm^2 of IAC at 400 nm	**~50% @ 1 C**	**~75% @ 1 C**	~0% @ 8 C	~0% @ 8 C