Experience with series-produced MCP-PMTs for the PANDA Barrel DIRC

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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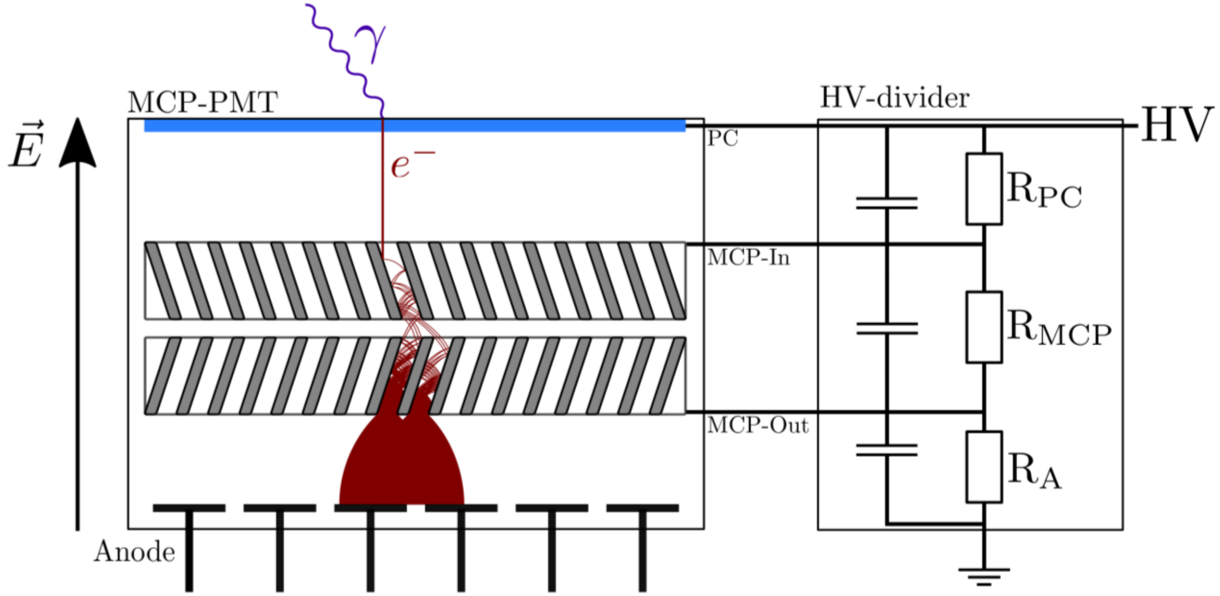
MCP-PMTs for the PANDA Barrel DIRC

Barrel DIRC in PANDA

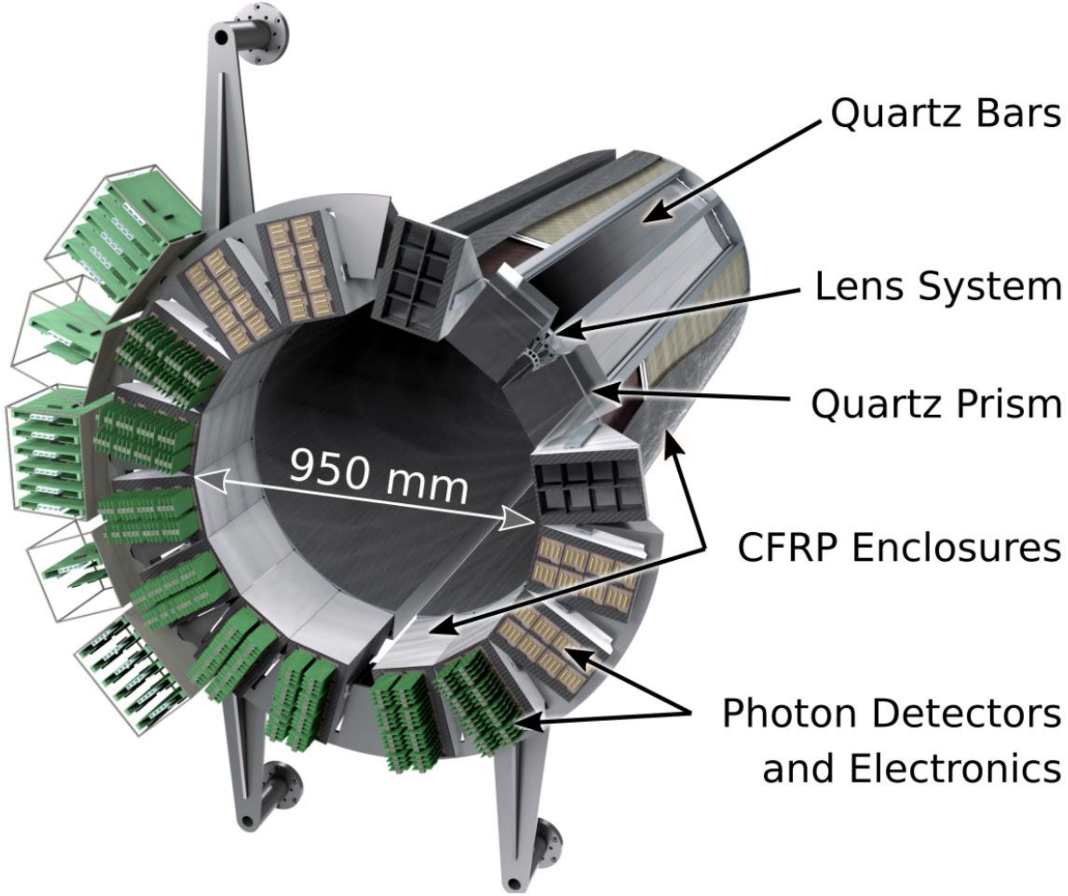
- Cherenkov based particle identification (π/K separation)
- See talk: “Status of the PANDA DIRC detectors” by A. Lehmann on Thursday 18.09.2025

- Photosensors in magnetic fields of ~1T

→ Microchannel Plate Photomultipliers (MCP-PMTs): Amplification of photoelectron in microchannels
→ very fast and resistant to magnetic fields



PANDA Barrel DIRC



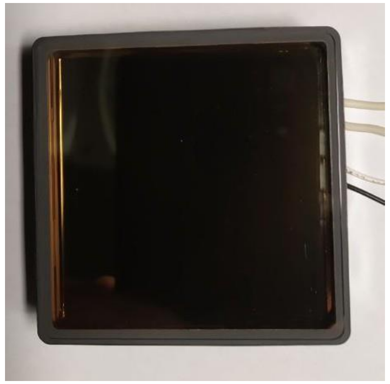
MCP-PMTs for the PANDA Barrel DIRC

- **128 MCP-PMTs for Barrel DIRC needed + 10 extra**
- In addition 27 subspec MCP-PMTs: some performance parameters below requirements

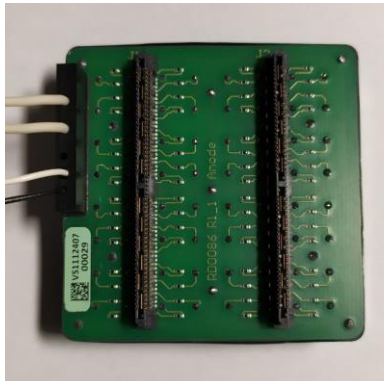
→ 165 MCP-PMTs ordered from PHOTONIS

Series produced MCP-PMTs
- PHOTONIS XP85112-S-BA
- Active area: 2x2 inch² (81% form factor)
- Anode: 8x8 pixel
- Backplane: 2x Samtech QRM8 connectors
- MCP pores: 10µm diameter
- ALD coated: 1x layer Al_2O_3, 1x layer MgO

PHOTONIS MCP-PMT



Front view



Back view

Quality assurance measurements in Erlangen

- Performance parameters investigated for **all** tubes:
  - Detective Quantum Efficiency DQE = **QE · CE** (Quantum Efficiency · Collection Effiency)
  - **Gain** and **rate capability**
  - **Uniformity** of gain and QE across active area
  - Internal parameters measured with TRB/DiRICH DAQ system: **Dark count rate, Afterpulse fraction, Time resolution**

- Important requirements measured for **some** tubes:
  - Immunity to **magnetic fields** ~1 Tesla
  - Photo cathode **lifetime** >10 years operation (5 C/cm² integrated anode charge (IAC))

Performance Parameters of MCP-PMTs

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- 106 of 165 tubes received, status August 2025
- Requirements of PANDA Barrel DIRC in table
  - Preferred specs defined in datasheet: ideal for PANDA Barrel DIRC → 10% of tubes in spec
  - Softened specs to increase acceptance rate: still acceptable → acceptance rate increased to ~60%
  - Out of specs: not suitable for PANDA

	Peak QE in 300-400nm range	QE MMR whole area	Gain MMR whole area	CE	DCR Hz / cm²	AP ratio	Rate capability rel. gain @ 500kHz/cm²	DQE
Datasheet specs	≥ 18%	≤ 1.5	≤ 3	≥ 95%	≤ 1000	≤ 1%	≥ 90%	≥ 16%
soft specs	if DQE ok	< 3	< 4	if DQE ok	< 5000	< 4%	> 80%	~ ≥16%

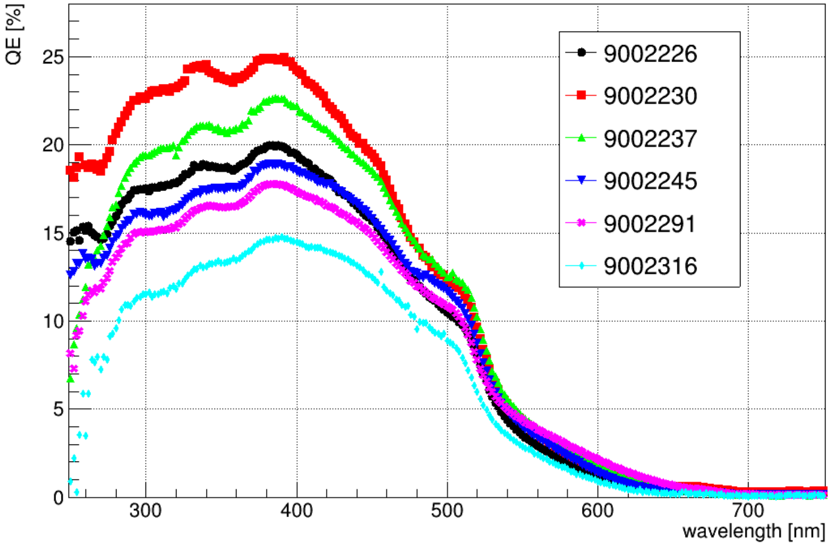
Measurement settings
(unless stated otherwise)
- 10^6 gain
- 4:10:1 voltage divider
- single photon illumination rates

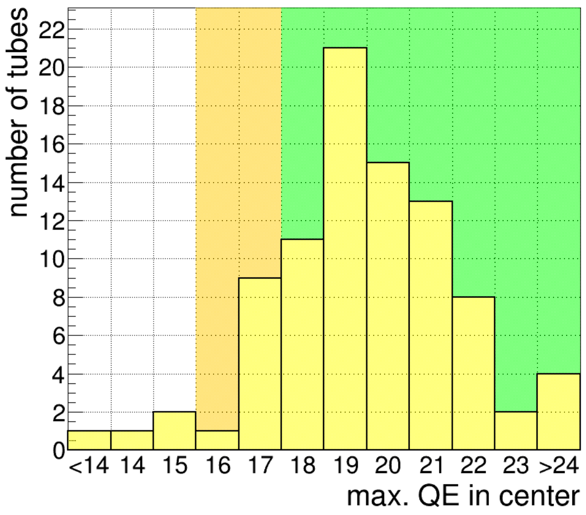
Detective quantum efficiency

Quantum efficiency (QE):

Probability of a photon producing a photoelectron

- Measured with 200V between PC and MCP, no amplification
- Dependent on wavelength
- **Requirement**: peak QE of >18% (>16% if CE=100%) between 300 – 400 nm
  → 84% (95%) in requirements
  (all measured tubes, not including broken tubes)
- Maximum QE at ~390nm for all sensors

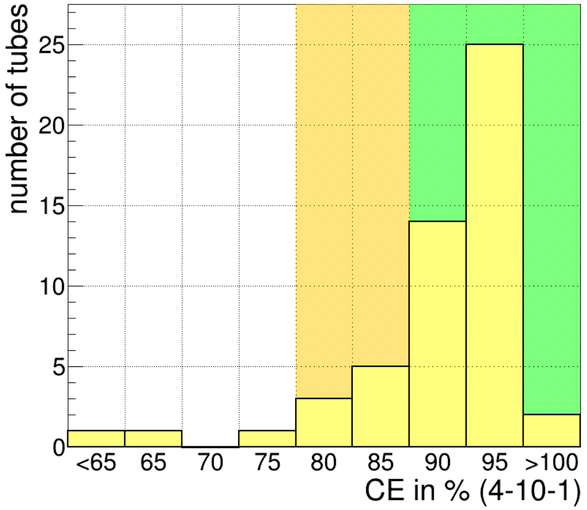




Collection efficiency (CE):

Probability of a photoelectron entering a pore and producing a signal

- **Requirement** (indirectly): DQE >16%
  → 80% of tubes CE >90%
- Not measurable for sensors with high fluctuations in leakage current

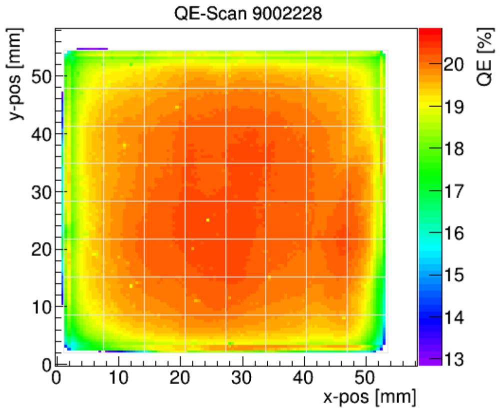


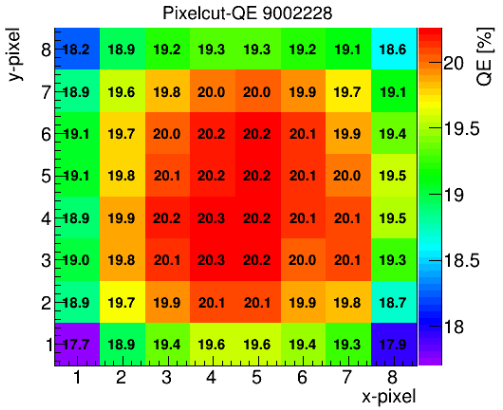
Uniformity of quantum efficiency

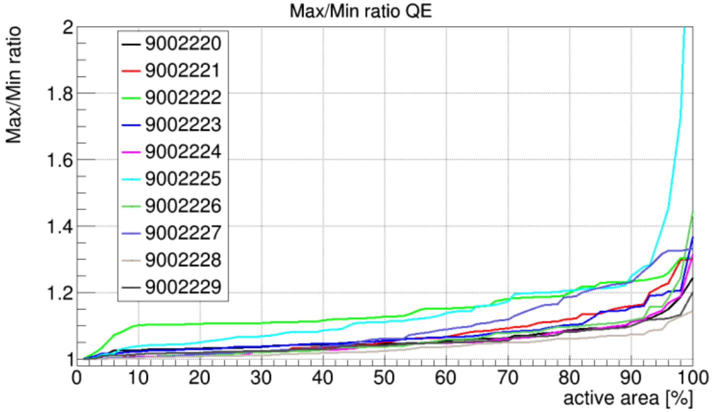
QE uniformity:

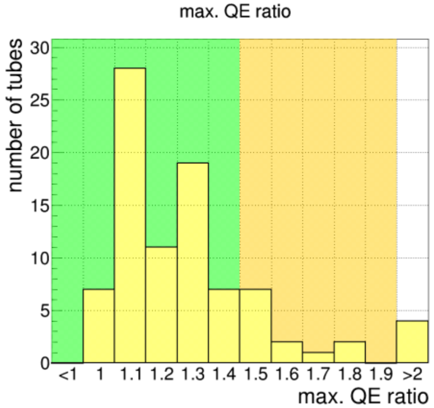
Distribution of QE across the active area

- Measured at 372nm
- Quantification: Max/min ratio:
  - Division of scan into 8x8 pixel grid with mean QE of each pixel
  - Division of maximum value by all other values sorted from lowest to highest
- **Requirement**: max/min <1.5 (<3)
  → 81% (98%) in requirement





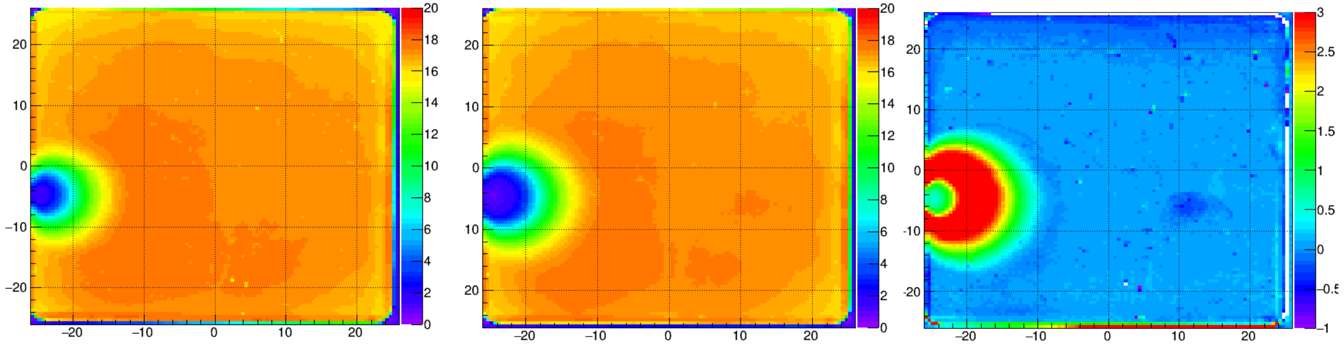




- Problem with some tubes:
  Vacuum micro leaks:
  Gas dissipates into tube and damages the photocathode
  → QE loss over time (without illumination)
  → Not usable

Example 9002291

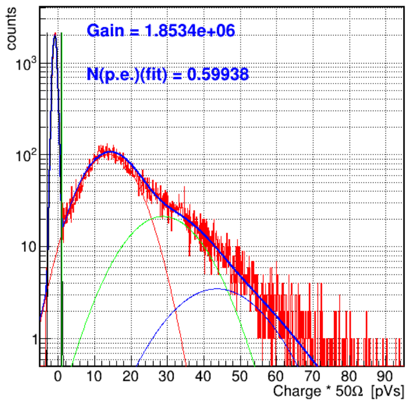
22. Oct. 2024 | 14. Jan. 2025 | Difference



Gain behavior

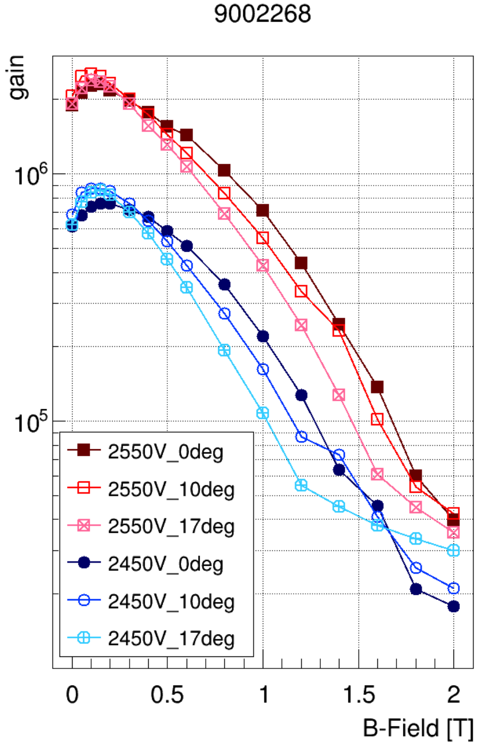
Amplification of photoelectron

- Determined from charge spectrum
- **Requirement**: Save operation at 10^6 gain in PANDA
- Magnetic field: gain loss of ~3 at 1 Tesla
  → 90% maximum gain of $> 3 \cdot 10^6$

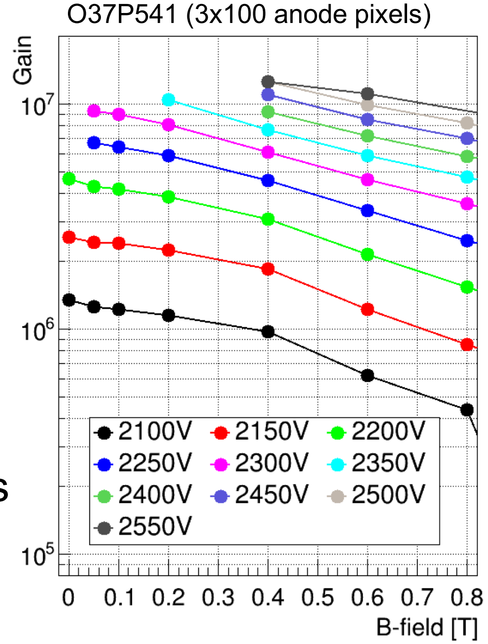


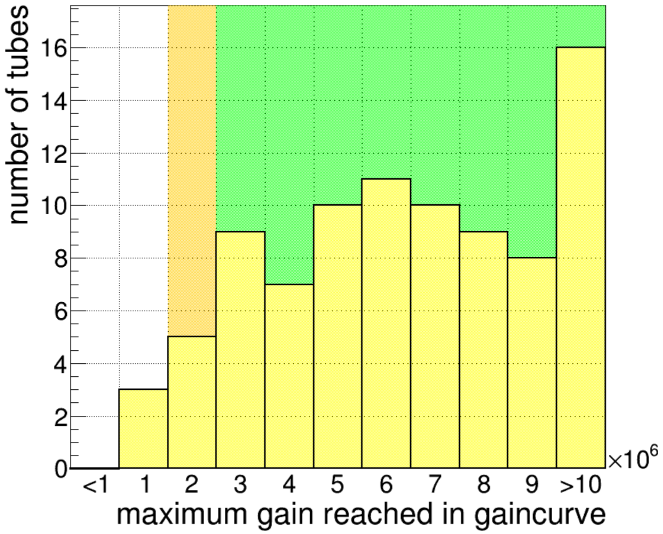
Charge spectrum of 9002249 at 2270V with 4:10:1 HV divider

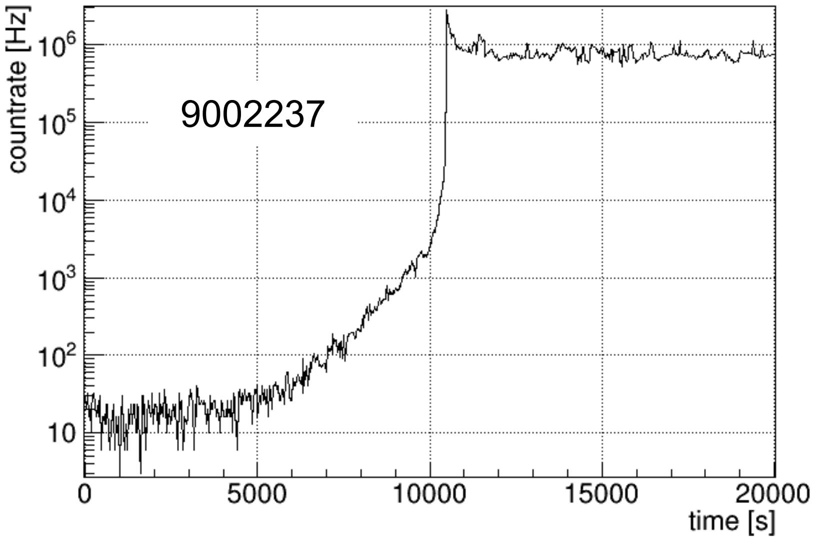
Fit function from:
E.H. Bellamy et. al.,
Absolute calibration and monitoring of a spectrometric channel using a photomultiplier,
https://doi.org/10.1016/0168-9002(94)90183-X



- Problem: <u>Escalation</u>
  - Self-sustaining mode of photon emission from MCP at massive rate
  - Locally and globally observed
  - Typically happens at high gains or high illumination rates
  - Improves in magnetic fields
  - Observed with all 2-layer ALD MCP-PMTs



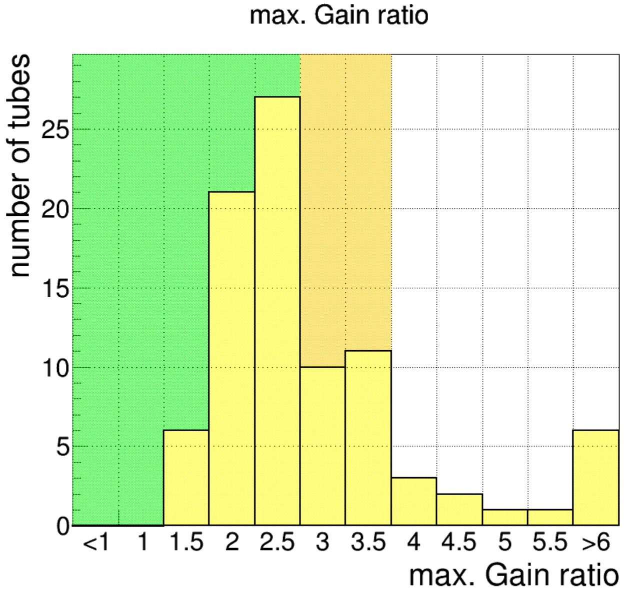


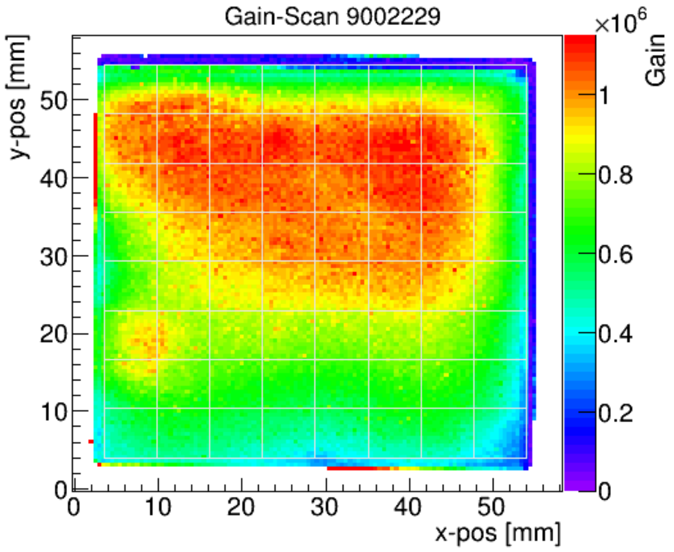


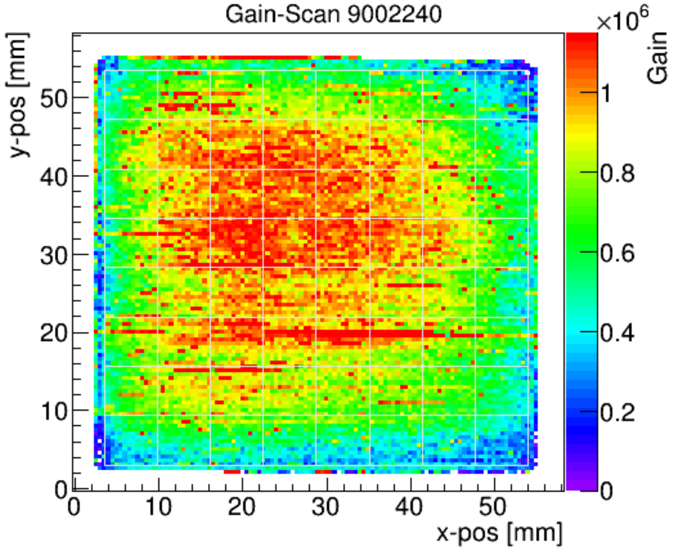
Gain uniformity

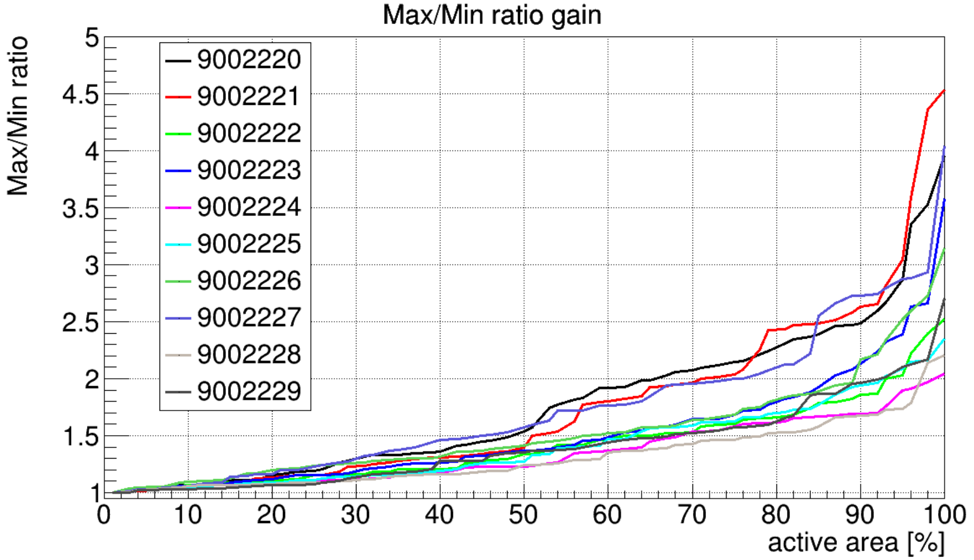
Distribution of gain across active area

- Quantification: Max/min ratio:
  - Division of scan into 8x8 pixel grid with mean gain of each pixel
  - Division of maximum value by all other values sorted from lowest to highest
- **Requirement**: max/min <3 (<4) for whole of active area
  → 60% (85%) in requirements
- Sensors with high fluctuating dark currents → noisy scans









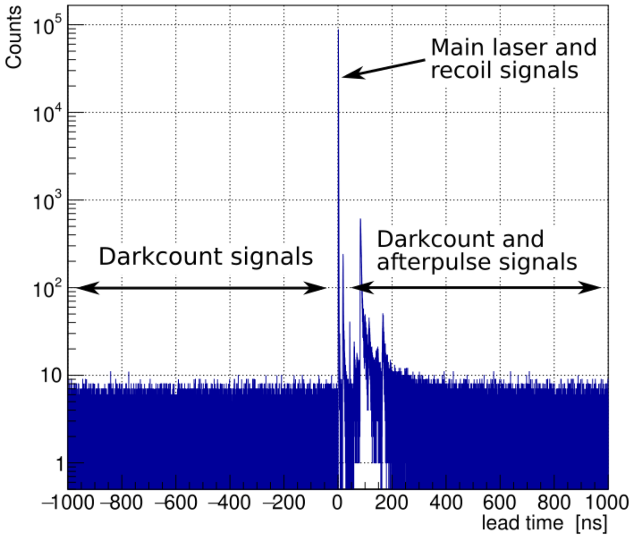
Dark count rate

<u>TRB/DIRICH DAQ</u>

- GSI designed
- FPGA based
- Multihit capable

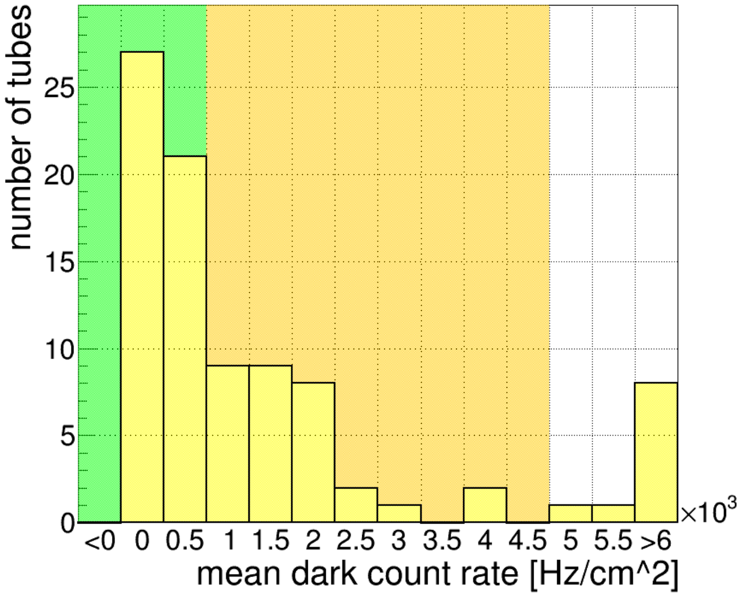
<u>Information obtained for every channel</u>

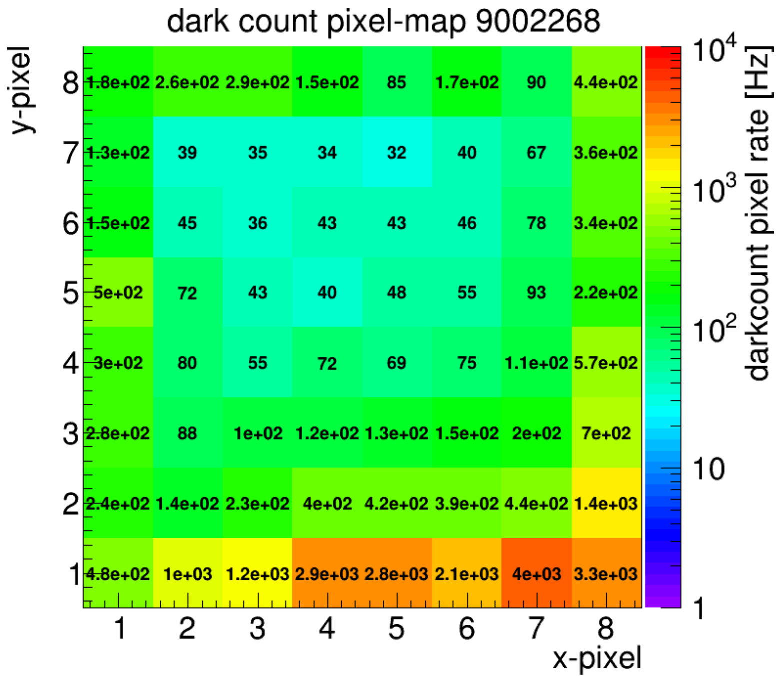
- Time over threshold
- Hit time
- Number of hits

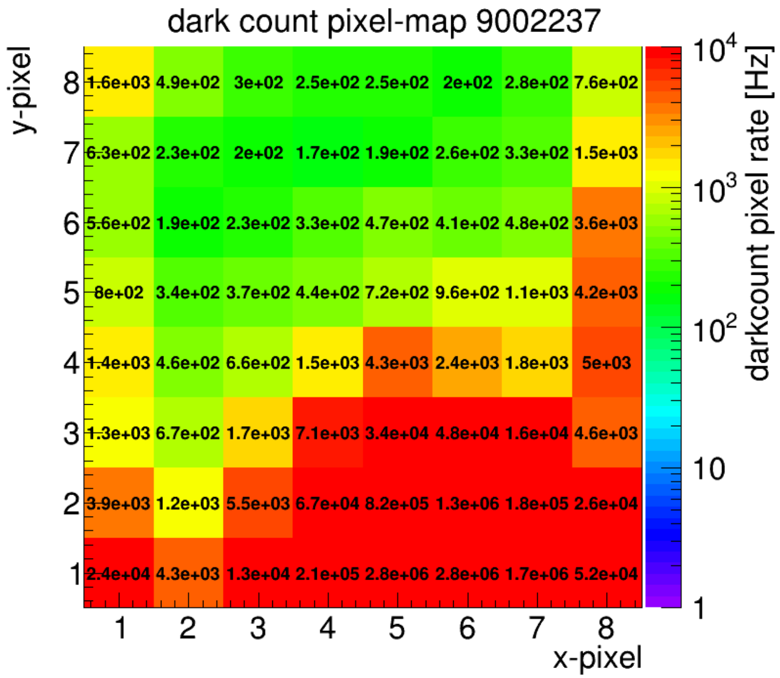


<u>Dark count rate:</u>

- Rate of hits before the laser trigger
- **Requirement**: <1kHz/cm² (<5kHz/cm²)
  → 54% (89%) in requirement
- Sometimes hot pixel at the rims (e.g. 9002268)
- Some tubes with very high DCR (>10kHz/cm²)
- 9002237: Count rates >1MHz/pix at bottom rim
  → enters local escalation in this region







Afterpulse probability

Afterpulses (AP):

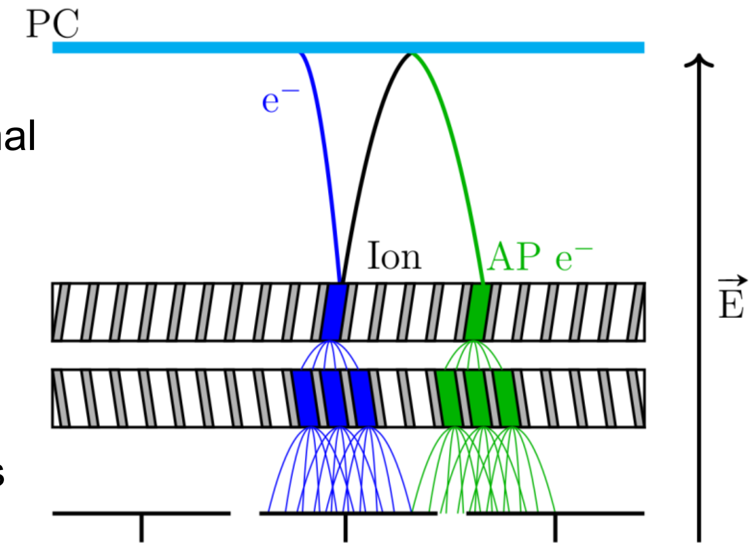
Ion that travels back to photocathode and creates a signal

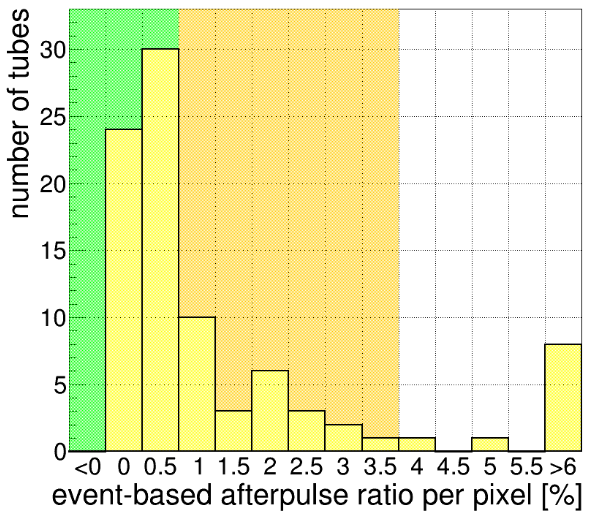
→ damages the photocathode (limits lifetime)
and leads to fake hits

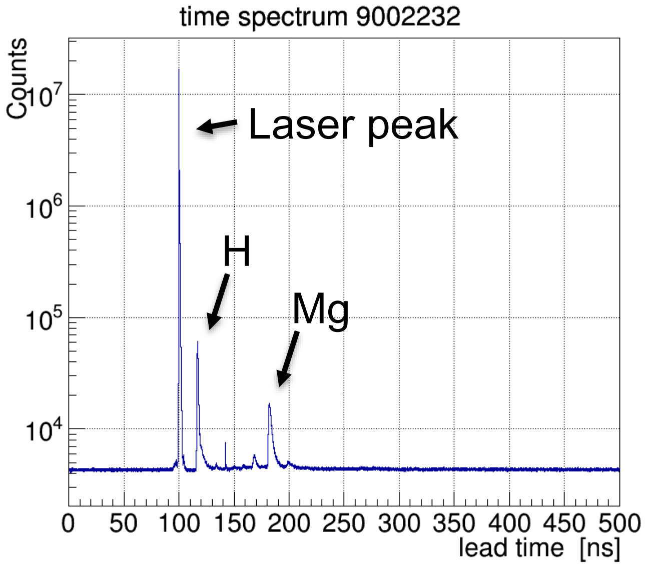
Afterpulse ratio:

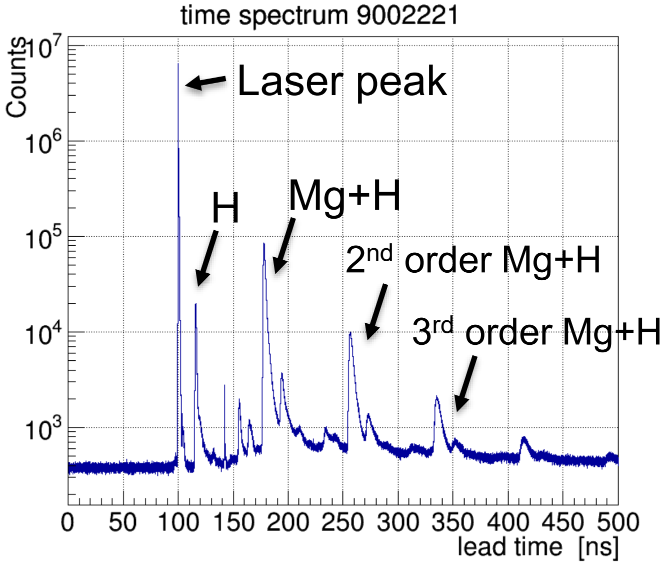
Ratio of number of events with one or more hits in time range 3-300ns after laser peak to total number of events

- **Requirement**: <1% (<4%) events with afterpulses
  → 61% (89%) in requirement
- Different afterpulse spectra observed:
  - Low AP ratio: only few peaks
  - Cascades of AP: AP ions create afterpulses
- Type and origin of most prominent peaks:
  (Best agreement with simulation)
  - Hydrogen from between the two MCPs
  - Magnesium from the back of the second MCP









Time resolution

Transit time spread (TTS): width of main laser peak

Root Mean Square (RMS): in time window -0.5ns to 2ns around laser peak

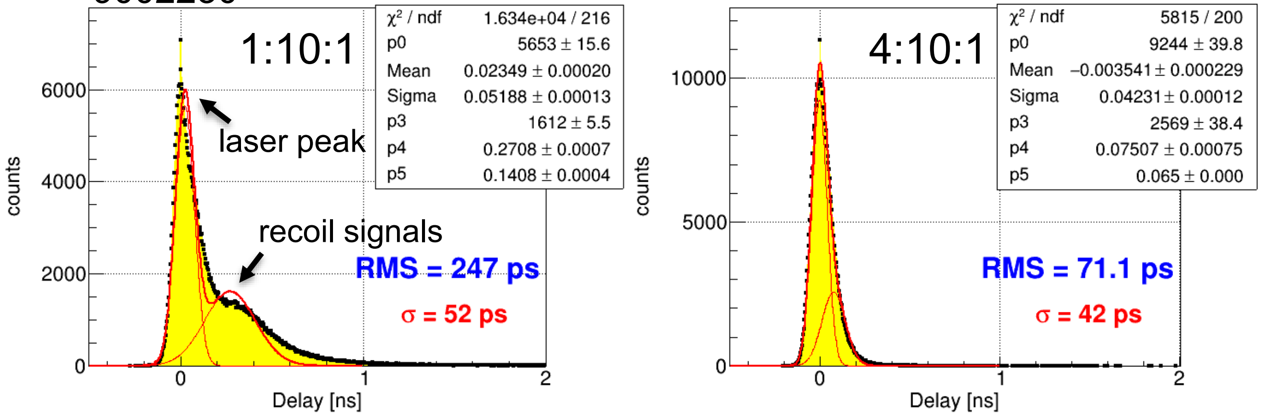
Measurement with the scope:

- Illumination of small spot (~1mm)
- Change of voltage divider from 1:10:1 to 4:10:1
  → Increase of the voltage between PC and MCP
  → Recoil peak shifted closer to main laser peak
  → Improved RMS (TTS hardly affected)

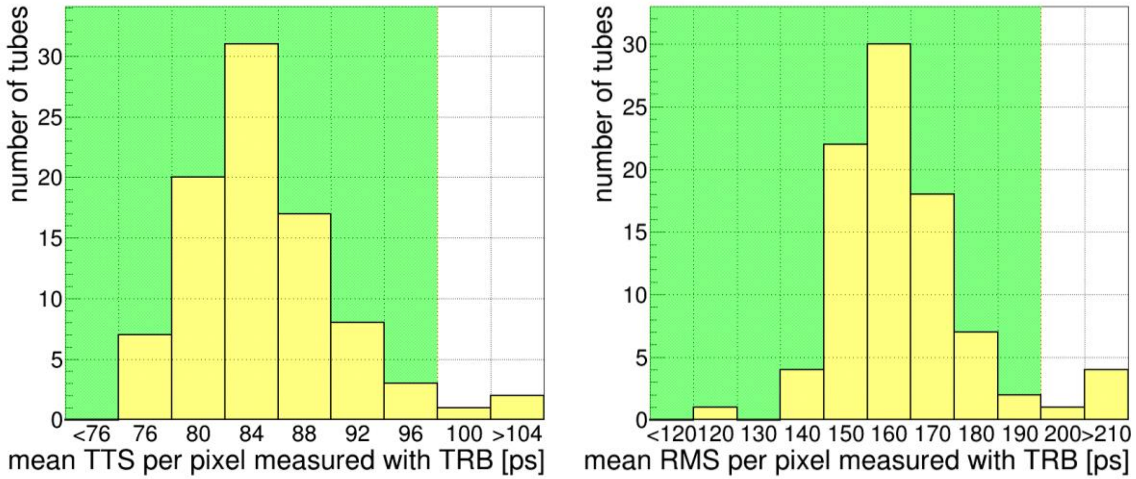
Measurement with the TRB system:

- Time resolution of whole pixel + DAQ system
  → worse than measurement with scope
- **Requirement**: <100ps TTS, <200ps RMS (TRB)
  → 95% in requirements
- Time resolution typically worse at the rims

9002230



TTS RMS

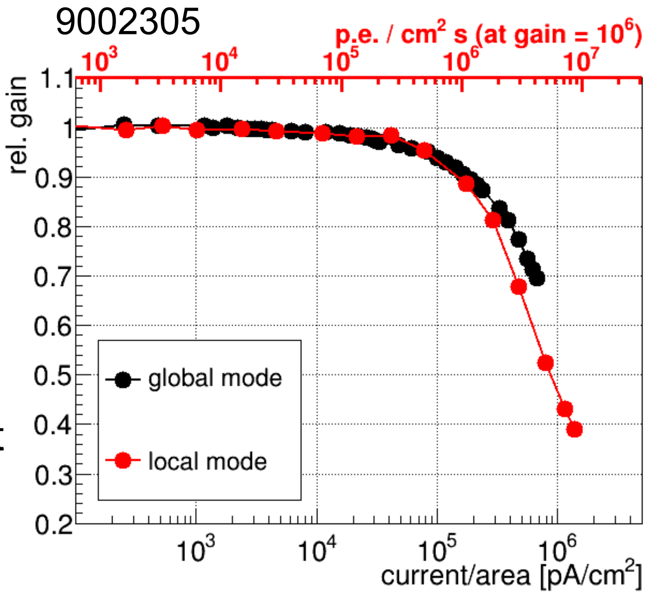


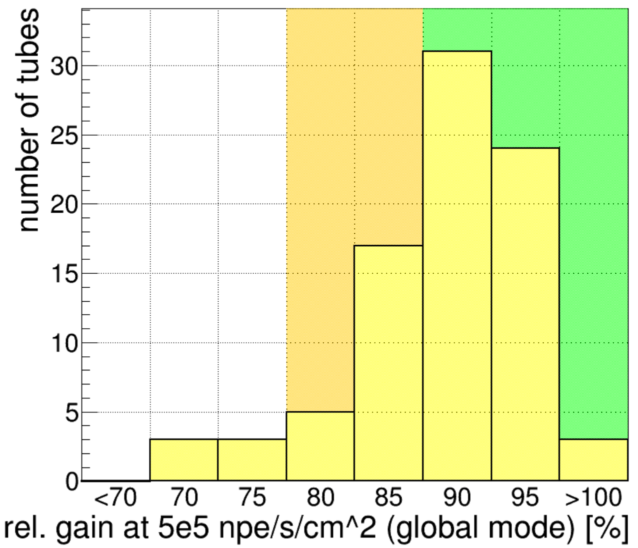
Rate capability

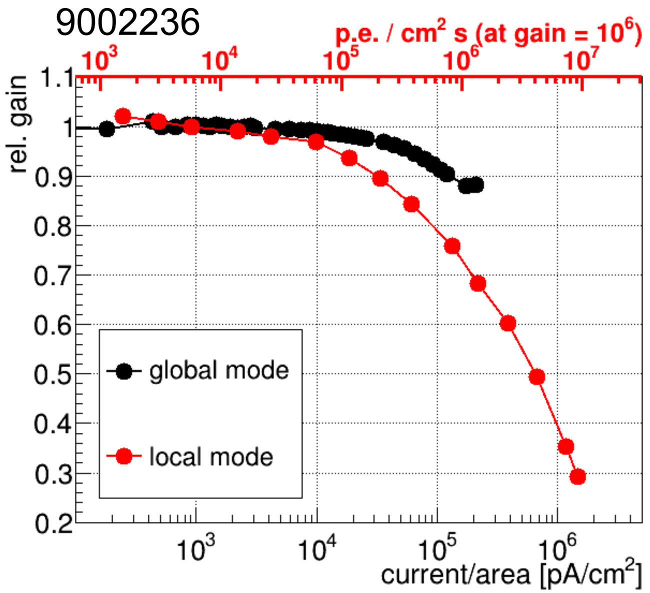
Gain drop at high illumination rates

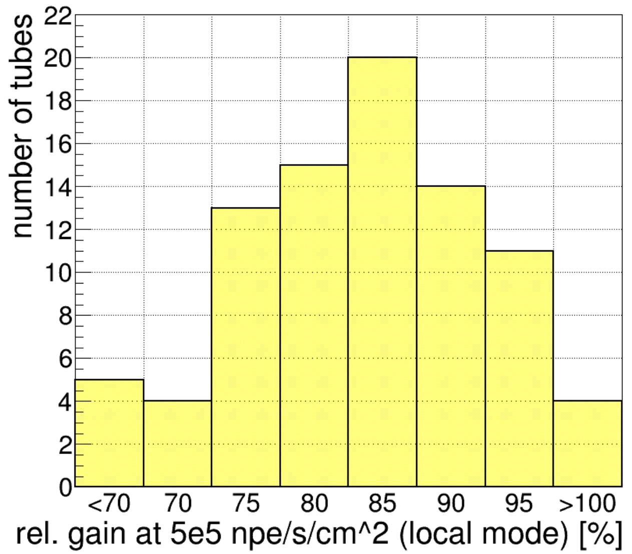
Measured in two modes:

- **Global mode**:
  - Illumination of whole active area
  - measurement of current at anode
  - **Requirement**: >90% (>80%) relative gain at photoelectron rate of 500 kHz/cm²
    → 67% (93%) in requirement
- **Local mode**:
  - Illumination of one pixel
  - Measurement of charge spectra
  - Typically similar or worse than global mode
- Differences in both modes not understood, potentially due to inhomegeneities in ALD layer thickness





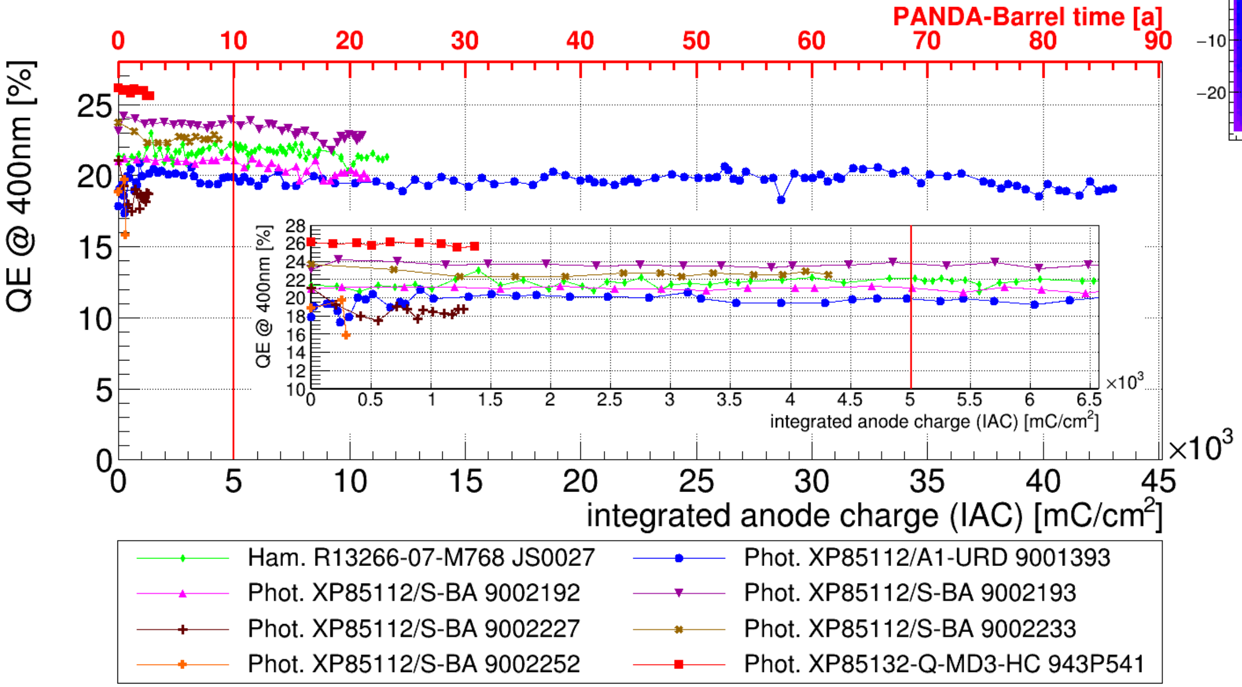




Lifetime

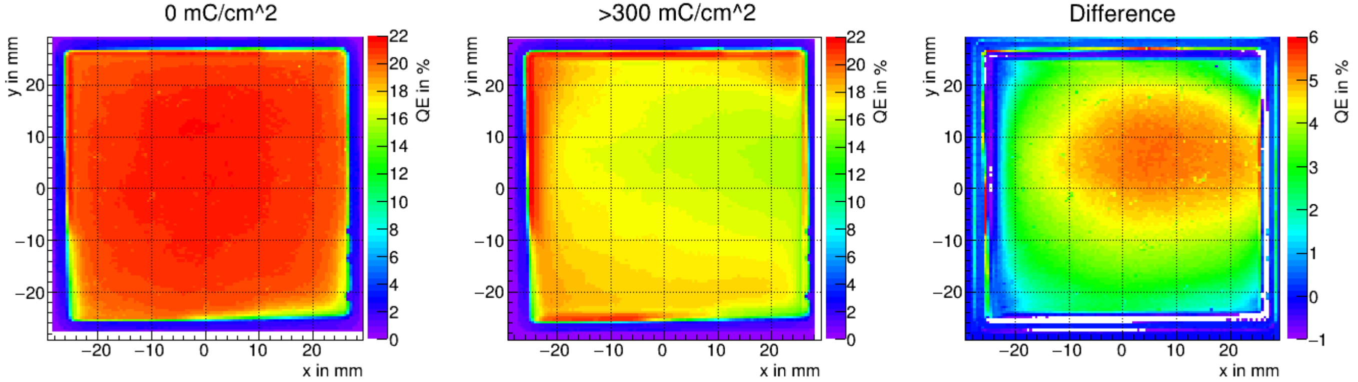
Update (status July 2025):

- 9001393 still without QE loss at ~45 C/cm²
- **Requirement**: >5 C/cm² without QE loss
- 9002192 and 9002193 at >10 C/cm²
  (same type as series production)
- Series production tubes 9002233 at 4.4 C/cm²
  and 9002227 at 1.4 C/cm² without QE loss

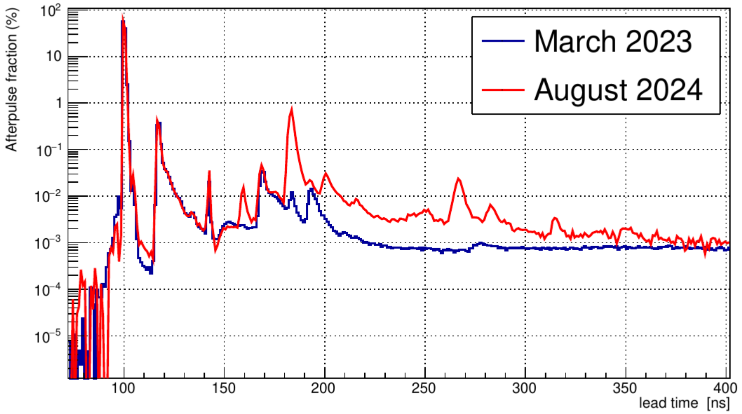


Observations:

- 9002252: entered escalation mode for a few weeks
  → significant QE loss
  → Not operable at 10^6 gain anymore



- 9002233: AP probability of Mg ions increased in the first few months (from 0.1% to 2.3%), now stable



Summary of performance

- 106 of 165 tubes received, status August 2025
- In spec: 10
- In soft specs: 53

} 63 accepted

- Subspec: 25
- Broken: 15
- Not categorized yet: 3

→ Acceptance rate of ~60%

- Main reasons for rejection
  - Subspec:
    - Gain max/min >4 (8 tubes)
    - DCR >5kHz/cm² (7 tubes)
    - Afterpulse ratio >4% (5 tubes)
    - Or multiple out-of-spec parameters
  - Broken:
    - Electrically shorted (5 tubes)
    - Escalation at low gains (4 tubes)
    - Vacuum micro leaks (4 tubes)
    - Instable MCP resistance (2 tubes)

<u>Main problems during measurements</u>

- High dark current
  → noisy gain scan
- High leakage current
  → noisy measurement of QE
  → CE measurement not possible
- Escalation
  → tube not usable in this mode

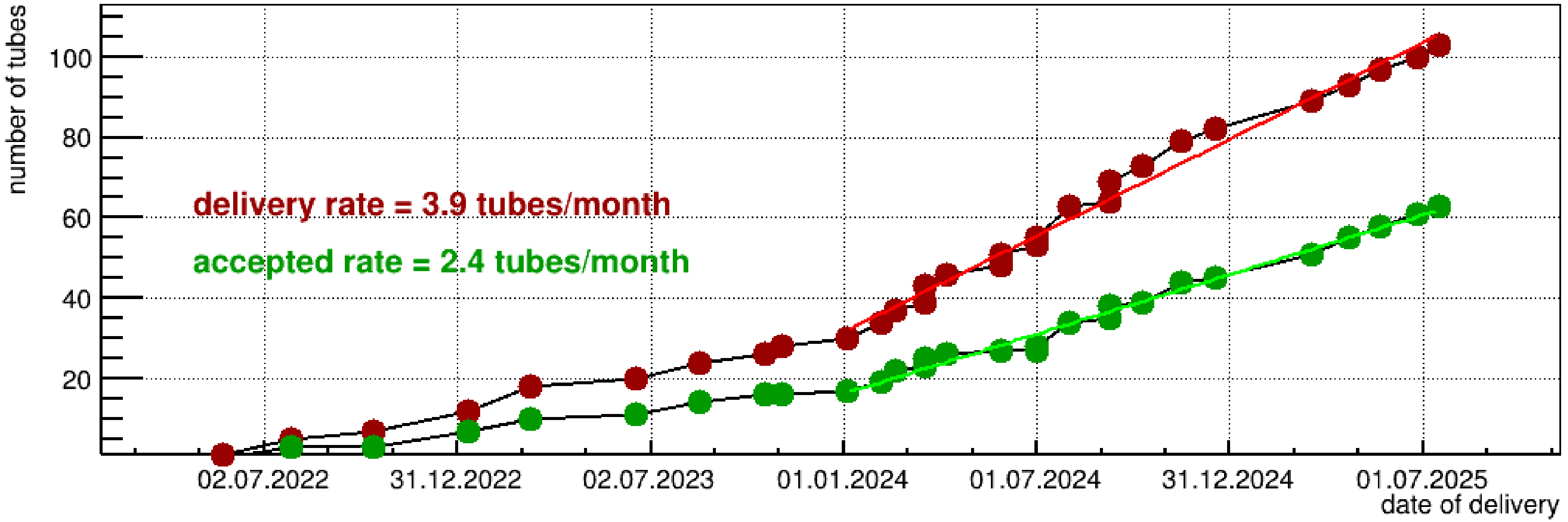
Summary of delivery

- First delivery: May 2022
- First delays due to escalation:
  Good communication with by PHOTONIS→ escalation mode shifted to higher gains

- Delivery rate ~4 tubes/month since January 2024 (expected rate 8-10 tubes/month)
- Acceptance rate ~60%
- QA in Erlangen limited to end of 2025

→ Series production ended in August 2025

- PHOTONIS stopped producing this kind of MCP-PMTs → new manufacturer must be found for PANDA



Further measurements

Rate capability:

- Dependency on MCP resistance
- Behavior at different gains
- Behavior in magnetic fields

Time resolution:

- Behavior at different rates

Probability of escalation:

- Operation voltage
- Dark count rate and afterpulse probability
- MCP resistance

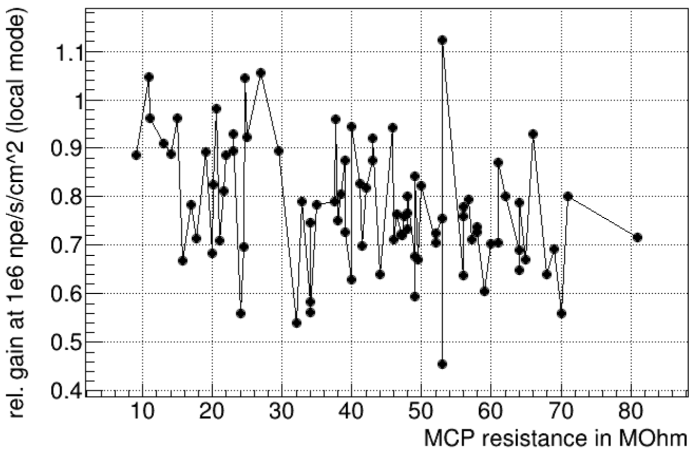
Fluctuating parameters:

- Gain
- Leakage and dark currents

Rate capability

Dependency on MCP resistance:

- Plot: relative gain at illumination rate of 1MHz/cm² vs. MCP resistance of all measured tubes
- Small improvement of rate capability at low resistances

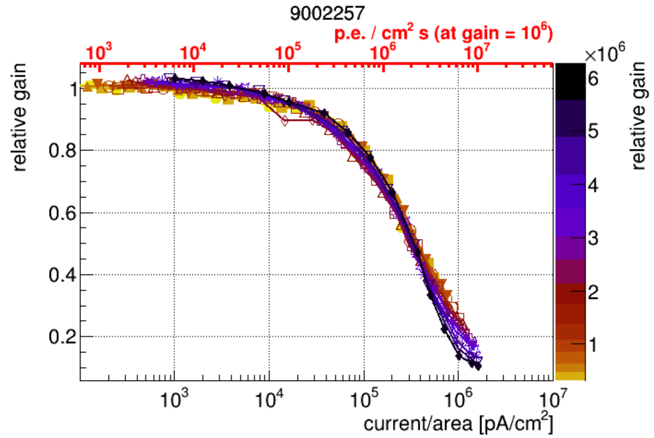


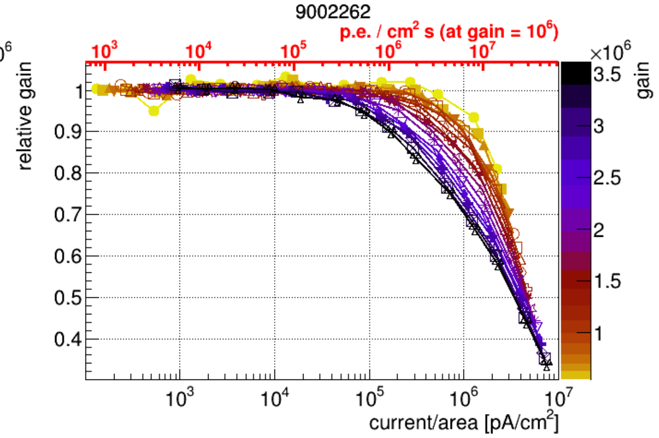
Behavior in magnetic fields:

- Focused illumination (spot size ~1mm): significantly worse rate capability already at small magnetic fields (50mT)
- Unfocused illumination: No effect on rate capability

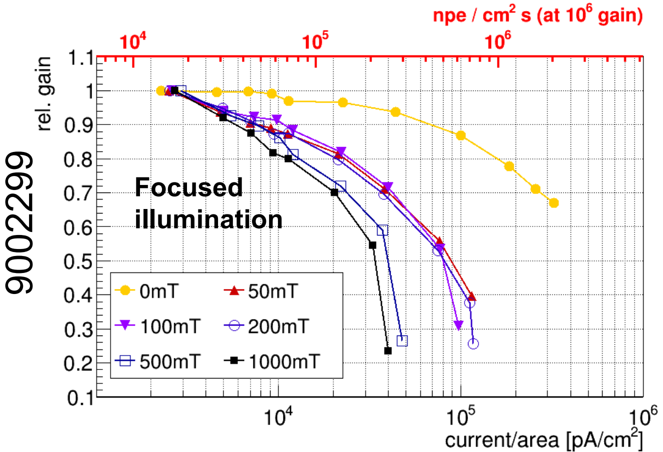
Rate capability at different gains:

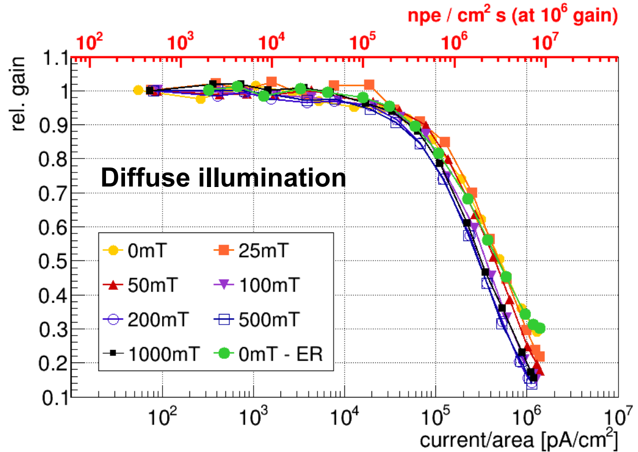
- Some sensors: significantly worse rate capability at higher gains
- Other sensors: no effect
- Not correlated to MCP resistance
- Potentially caused by inhomogeneities of ALD layer thickness





9002299





Time resolution at different rates

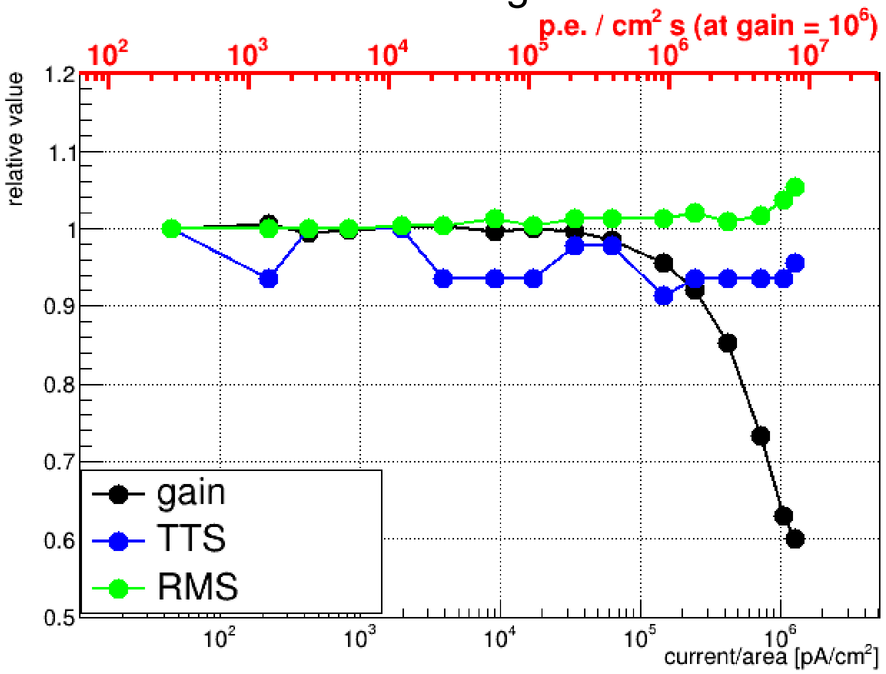
<u>Time resolution at different illumiation rates:</u>

- Measured with 1:10:1 voltage divider

<u>Observations:</u>

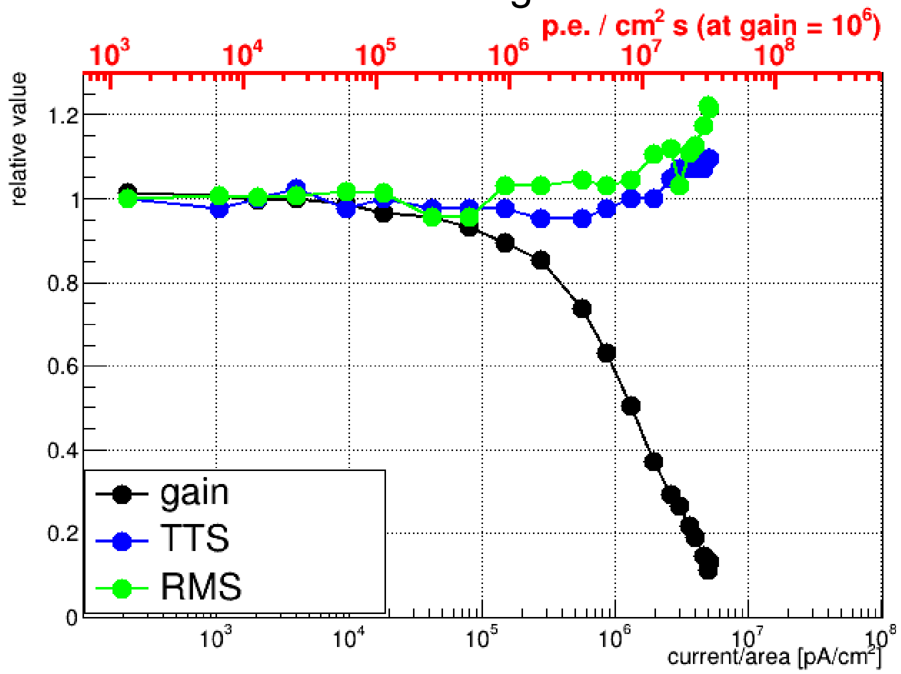
- Constant time resolution up to high rates ($> 10^6\ \frac{\text{p.e.}}{\text{cm}^2\text{s}}$)
- At very low relative gains: smaller signal height → worse signal-to-noise ratio → worse time resolution

$1 \cdot 10^6$ gain



9002302

$5 \cdot 10^6$ gain

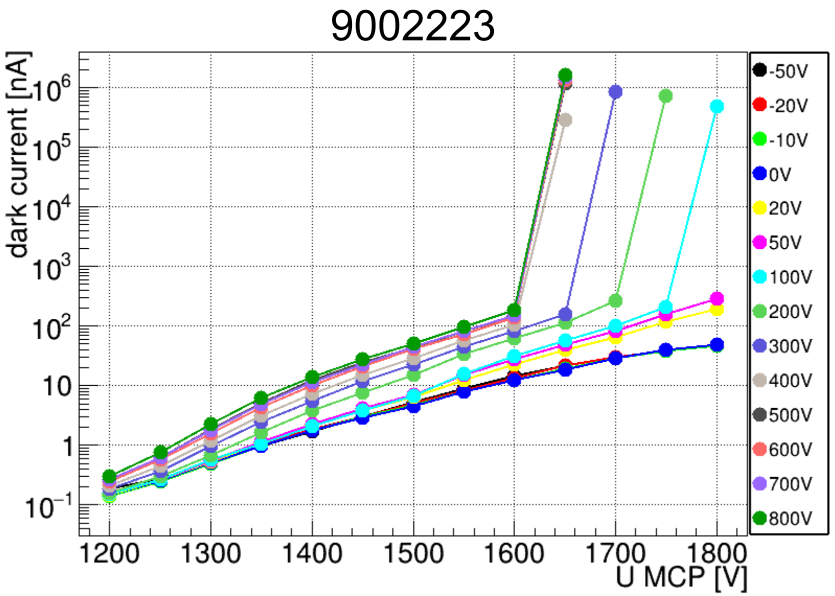


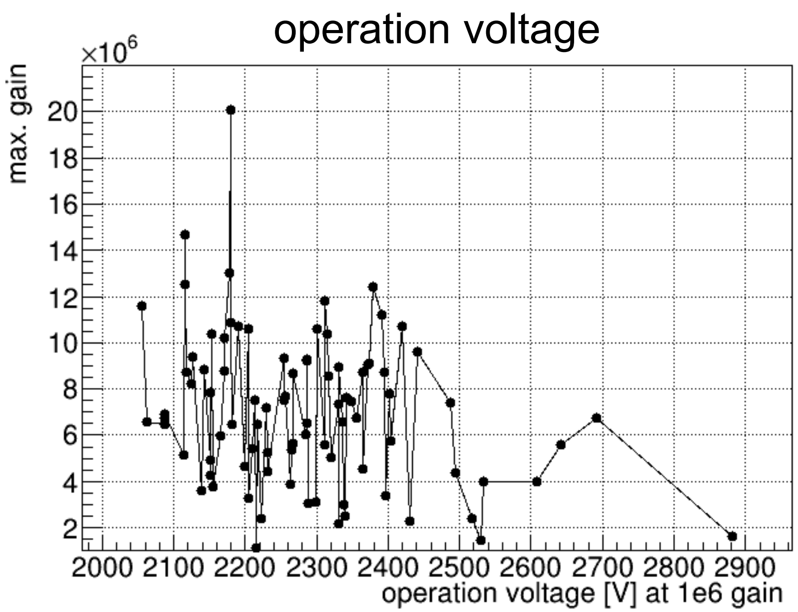
Onset of escalation

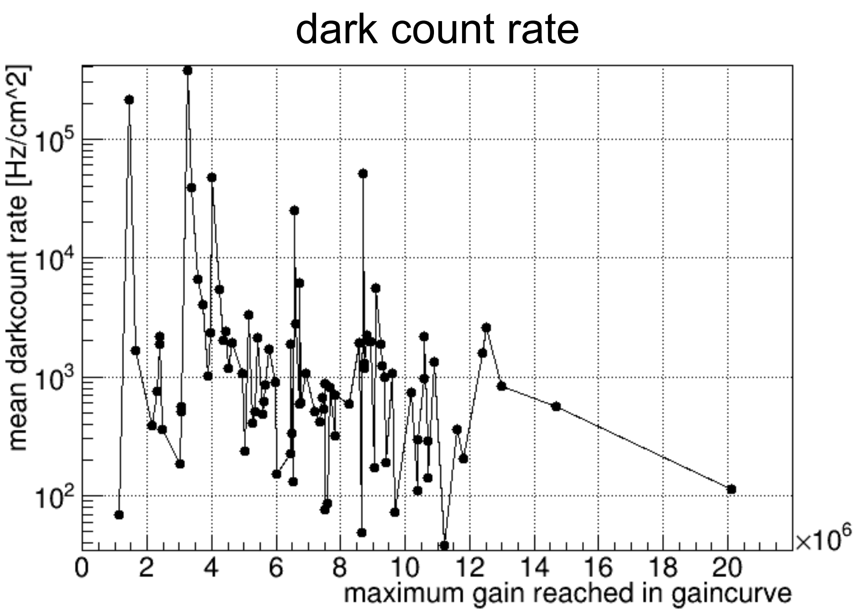
Higher maximum gain before escalation for:

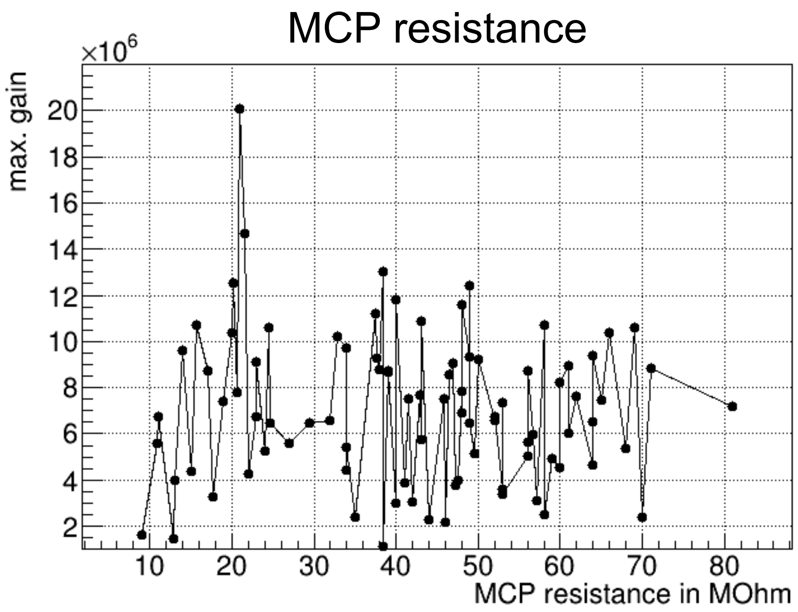
- Smaller operation voltage for 10^6 gain
- Smaller dark count rate
- Smaller afterpulse ratio

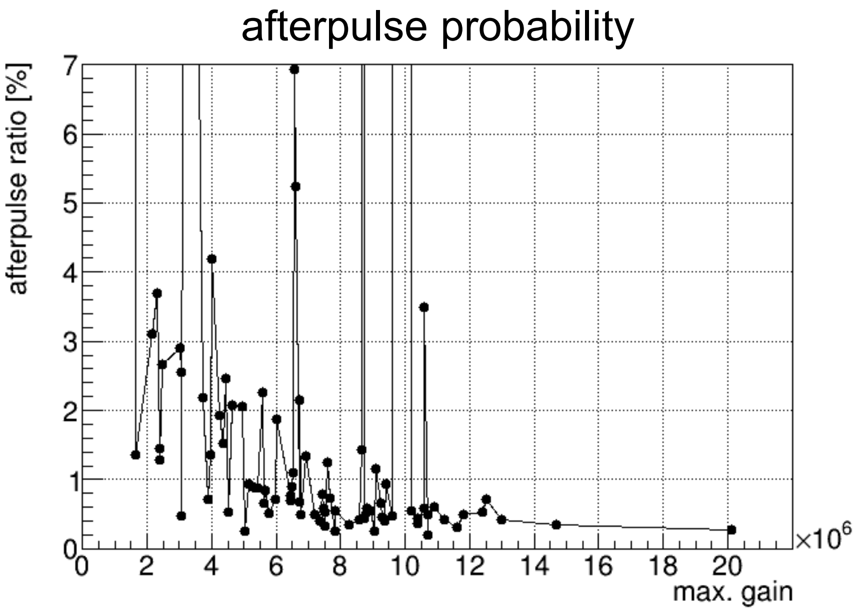
- MCP resistance → no impact on escalation











Fluctuations of gain and currents

<u>Spikes in gain</u>:

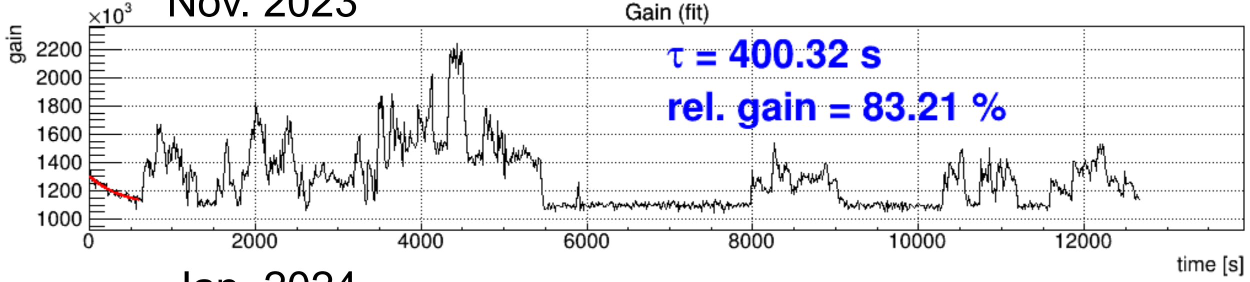
- Some tubes: unstable gain, increase by up to a factor of 2
- Spikes disappear after a few months

→ No problem for PANDA experiment

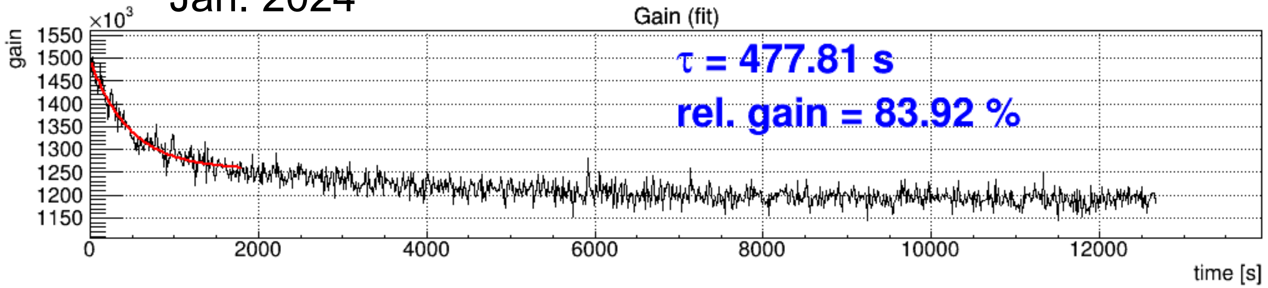
→ Some measurements not possible with spikes

- Cool down constant τ (exponential) similar for all tubes

Nov. 2023



Jan. 2024



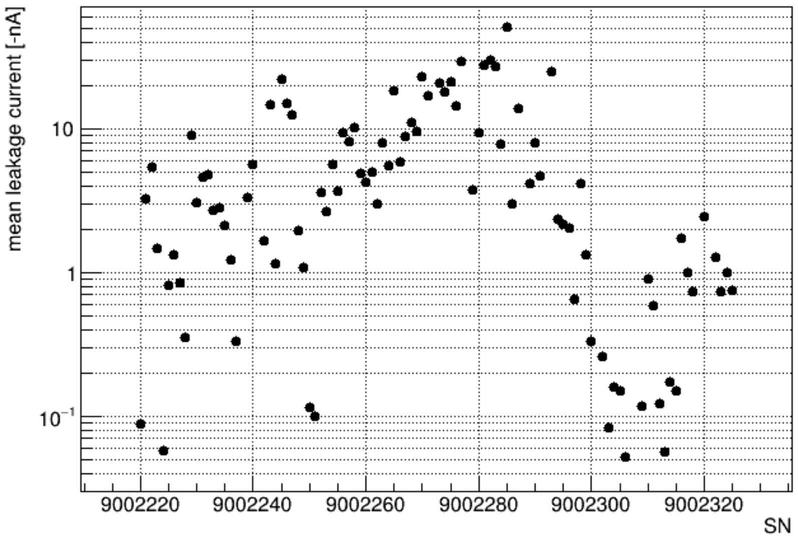
<u>Leakage and dark current</u>:

Leakage current: Current between PC and MCP without illumination

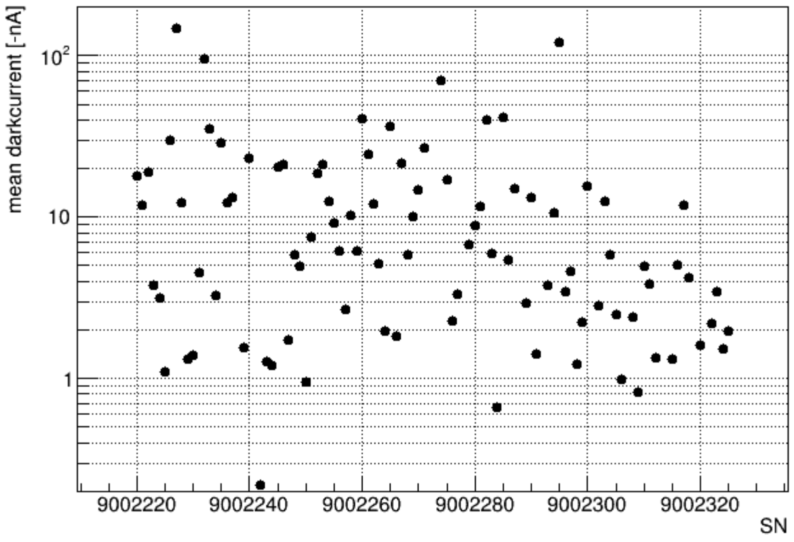
Dark current: Anode current without illumination

- Directly after delivery: some tubes with dark and leakage currents of 10-100nA → noisy measurements
- Leakage and dark current decreases with time (~ weeks to months)

mean leakage current



mean darkcurrent



Summary

Delivery:

- 106 tubes since May 2022
- Delivery rate: 4 tubes/month
- Series production ended now

Performance:

- 63/103 tubes usable for PANDA
  → Acceptance of ~60%
- Enough tubes for prototype sector of PANDA Barrel DIRC
- Main reason for rejection:
  - Low gain uniformity
  - High dark count rates
  - High afterpulse ratio
  - Escalation

Lifetime:

- Best performing tube at 45 C/cm²
- Tendering tubes from PHOTONIS at >10 C/cm²
- Series production tube at 4.4 C/cm² without QE loss
  → will probably reach requirement

Further investigations:

- Rate capability
  - Better rate capability at small MCP resistances
  - Dependency on applied gain for some sensors
- Time resolution at high illumination rates unchanged
- Onset of escalation
  - Later for lower DCR, AP ratio, operation voltage
  - Not dependent on MCP resistance
- Fluctuations of gain, dark current and leakage current
  → influence measurements