Performance of the most recent MCP-PMTs

Merlin Böhm, A. Lehmann, D. Miehling, M. Pfaffinger, S. Krauss

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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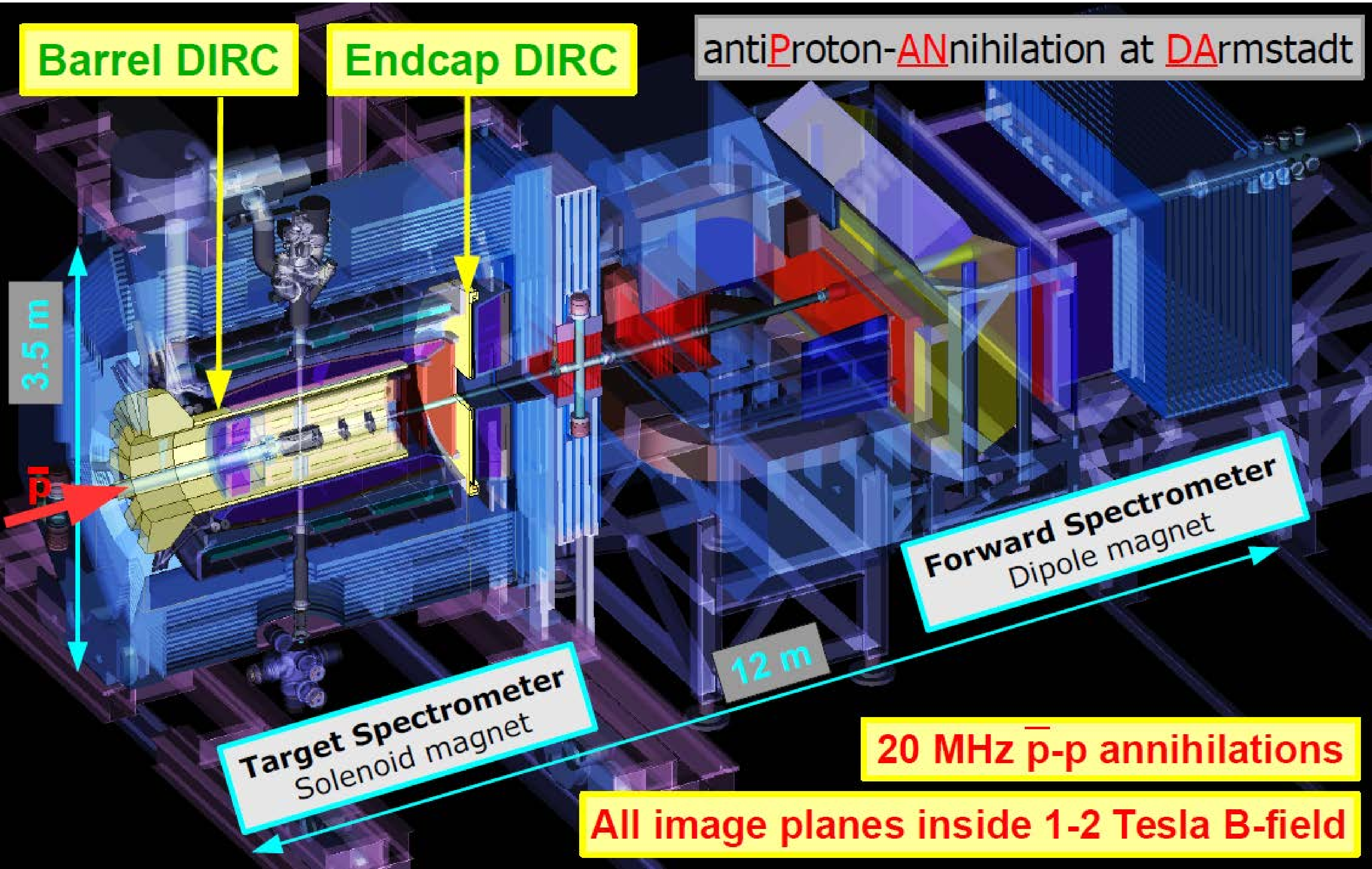
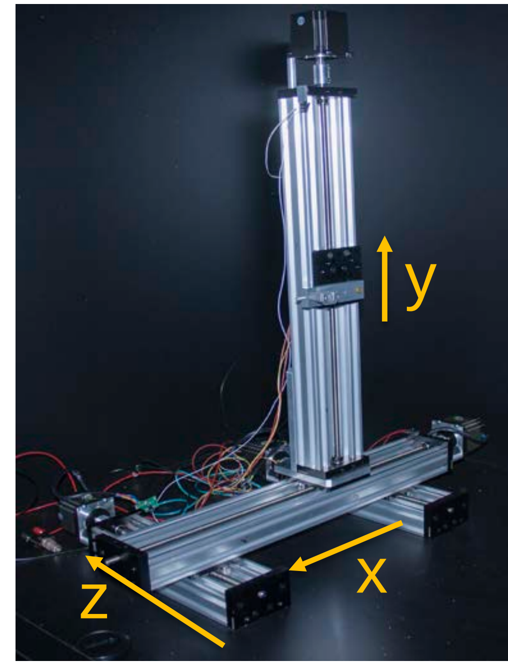

Barrel DIRC
Endcap DIRC
antiProton-ANnihilation at DArmstadt
3.5 m
p̄
Target Spectrometer
Solenoid magnet
12 m
Forward Spectrometer
Dipole magnet
20 MHz p̄-p annihilations
All image planes inside 1-2 Tesla B-field

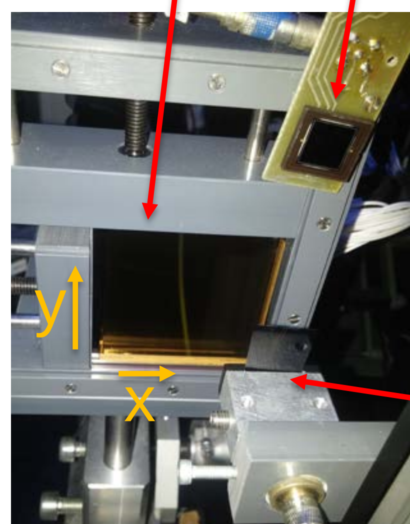
MCP-PMTs for PANDA DIRCs

- 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
  - Low dark count rates and good rate stability
  - Excellent time resolution <50 ps Peak (σ) (<120 ps RMS)
  - Meanwhile sufficient lifetime to survive PANDA (ALD and modified cathodes)
- Barrel DIRC
  - Photon rate: ~200 kHz/cm^2
  - 10 years anode charge: ~5 C/cm^2
  - Pixel size: ~ 6 x 6 mm^2
- Endcap DIRC
  - Photon rate: up to 1 MHz/cm^2
  - 10 years anode charge: >5 C/cm^2
  - Pixel size: ~ 0.5 x 16 mm^2

Measurement setups and measured parameters

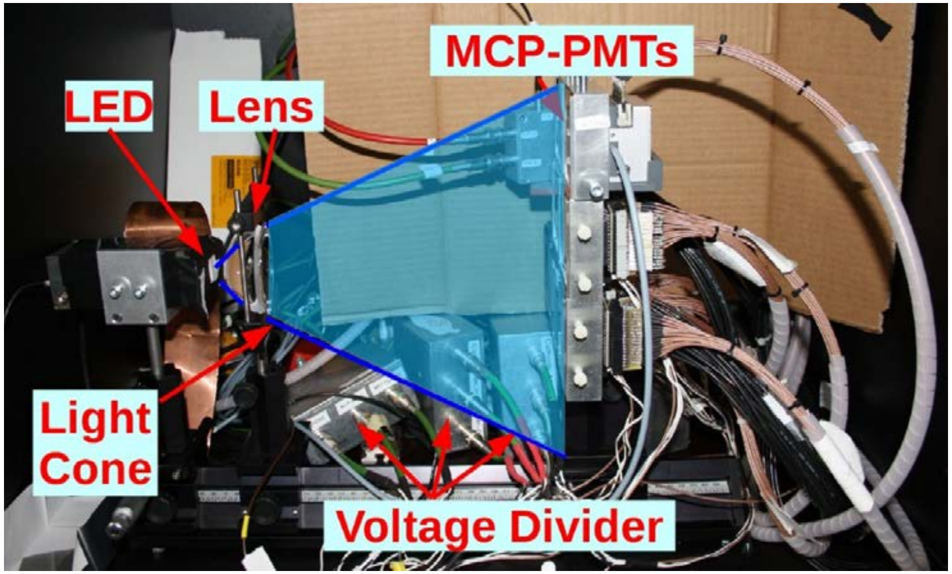
- Surface scans: PILAS Laser with micro focus attached to a 3-axis stepper
- FPGA based DAQ: TRB, Padiwa
  - Padiwa FEE for discrimination
  - TRB for time and TOT measurement
  - Multihit capability
- TRB3 and Padiwa3:
  - Signal height distribution (important for setting the threshold)
  - Crosstalk, charge cloud width and recoil electron behavior
  - For each Pixel: time resolution, darkcount rate and afterpulse probability





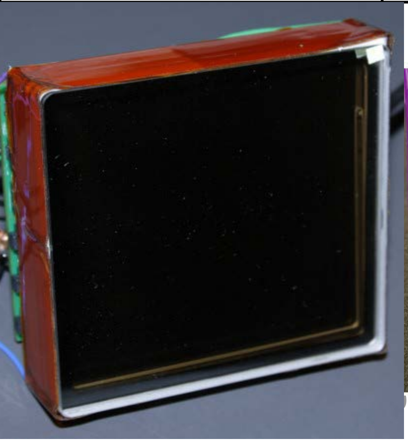
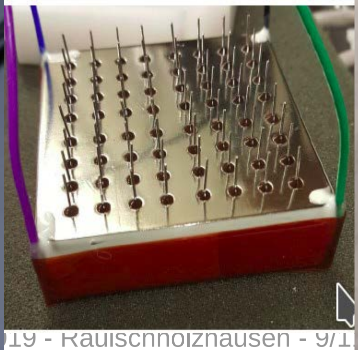
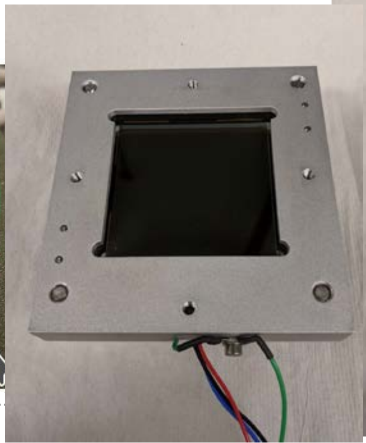
Measurement setups and measured parameters

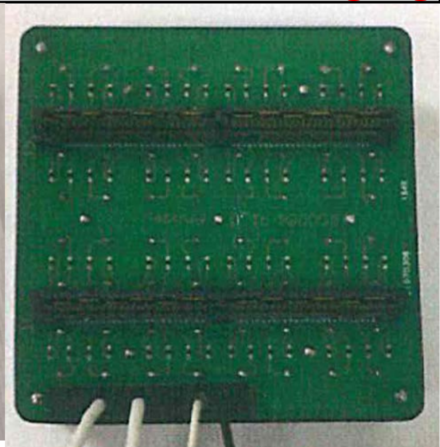
- Oscilloscope: LeCroy WavePro 7300A
  - Time resolution and gain vs. voltage
- With a Keithley 6487 Picoampere Meter:
  - Rate stability
  - Surface scans of quantum efficiency (QE) and gain distribution
- QE vs. Wavelength measurements using a Xenon arc lamp and monochromator
- Lifetime measurements:
  - Aging of MCP-PMTs with a blue LED
  - Continuous monitoring of pulse heights and LED light intensity



Investigated MCP-PMTs in this talk (all with ALD)

	Hamamatsu	Photek	Photonis
Model	R13266-07-M64M	PMT253	XP85112
S/N	YH0250	A1171005	9002150
Pore size (μm)	10	15	10
Pixels	8x8	8x8	8x8
Active area mm²	51x51	53x53	53x53
Total area mm²	61x61	59x59	59x59
Geom. Eff. (%)	70	81	81
Peak QE	28% @ 380 nm	12% at 340 nm	20% at 400nm
Comments	no film	"over-cooked" PC, metal housing	Modified backplane to reduce crosstalk and ringing

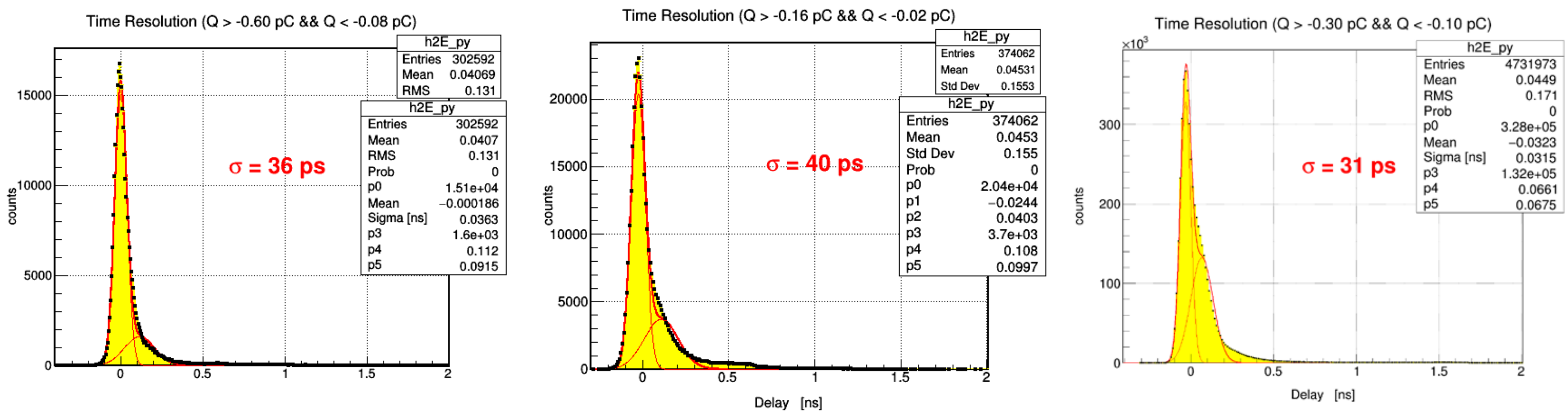






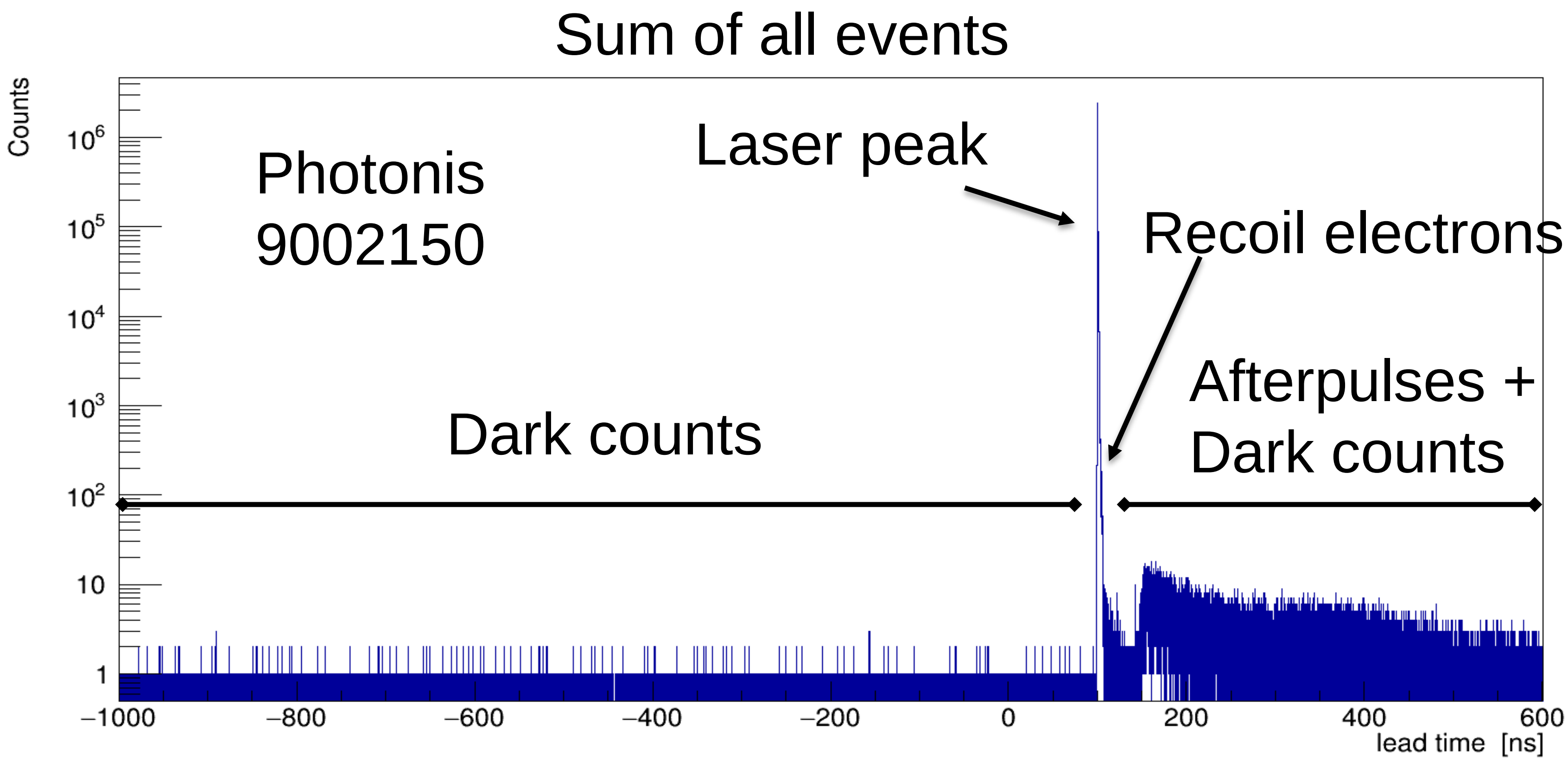
Time resolution measurements with Oscilloscope

- Oscilloscope: LeCroy WavePro 7300A
- RMS between -0.5 ns and 2 ns around laser peak

	Hamamatsu	Photek	Photonis
	YH0250	A1171005	9002150
Time resolution RMS	131 ps	155 ps	171 ps
Peak time resolution (σ)	36 ps	40 ps	31 ps



TRB measurements – Time spectrum

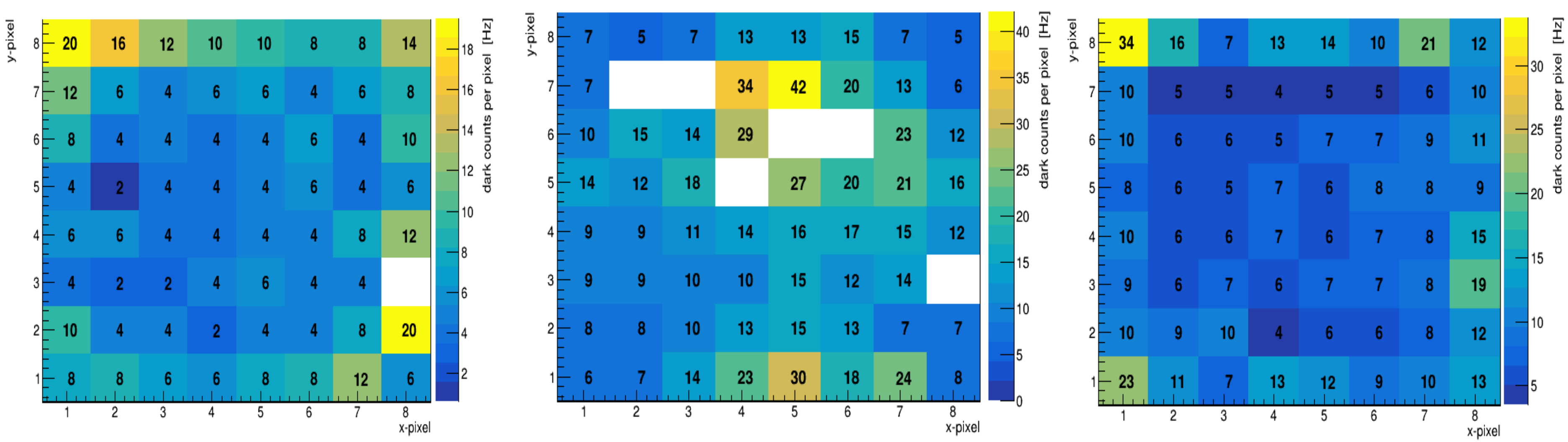


- Measured time delay between laser pulse and pixel response
- Laserpeak for all channels shifted to 100 ns for easier analysis

Darkcount rate comparison using TRB DAQ

- Darkcount rate corrected for missing Channels in the DAQ
- Threshold set to 0.1-0.2 p.e., ~1e6 Gain

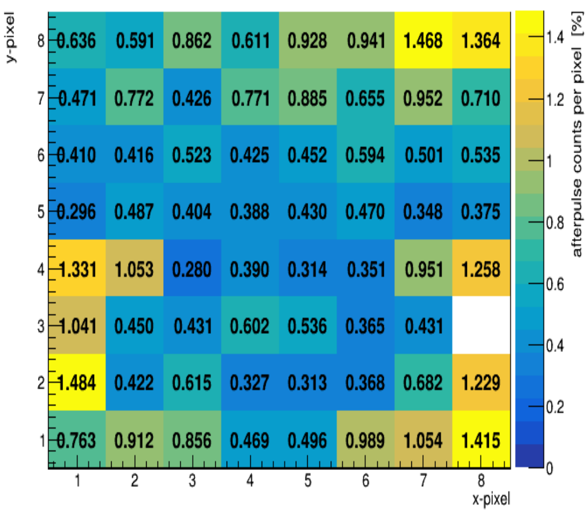
	Hamamatsu	Photek	Photonis
	YH0250	A1171005	9002150
Integrated DC rate	430 Hz	907 Hz	593 Hz
Average Pixel DC rate	7 Hz	14 Hz	9 Hz

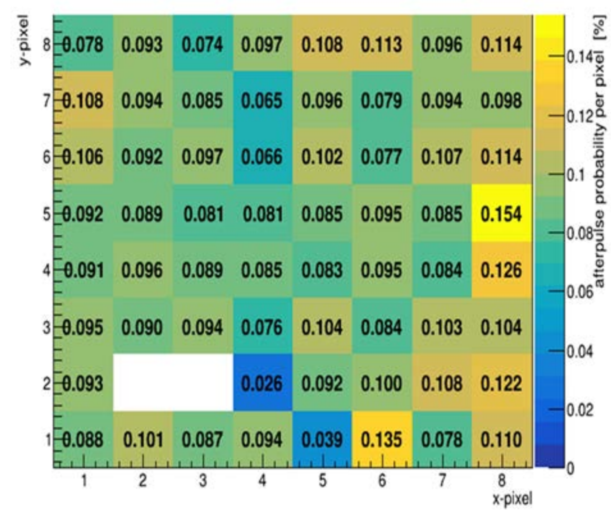


Afterpulse probability comparison using TRB DAQ

- Afterpulse probability corrected for missing channels in the DAQ
- Threshold set to 0.1-0.2 p.e., ~1e6 Gain

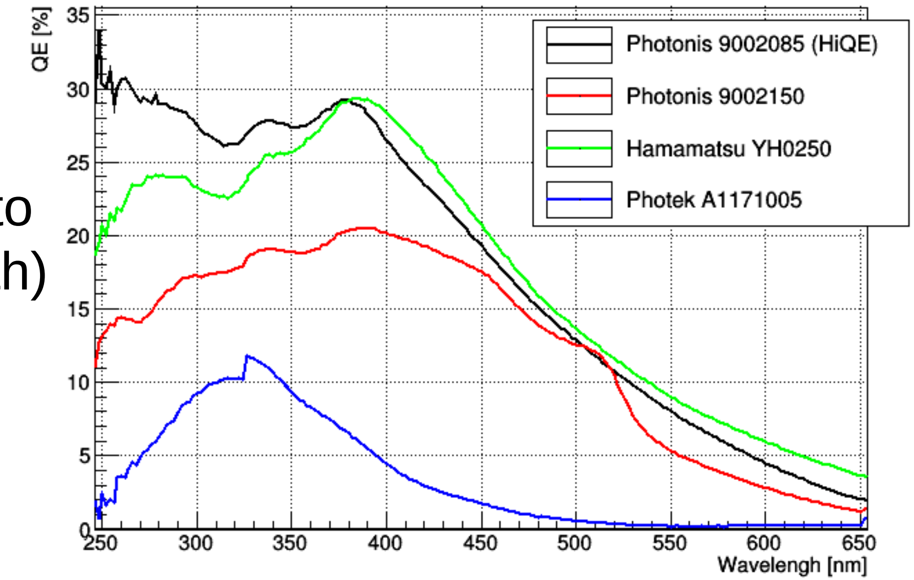
	Hamamatsu	Photek	Photonis
	YH0250	A1171005	9002150
Afterpulse probability per pixel (%)	0,671	0,065	0,093

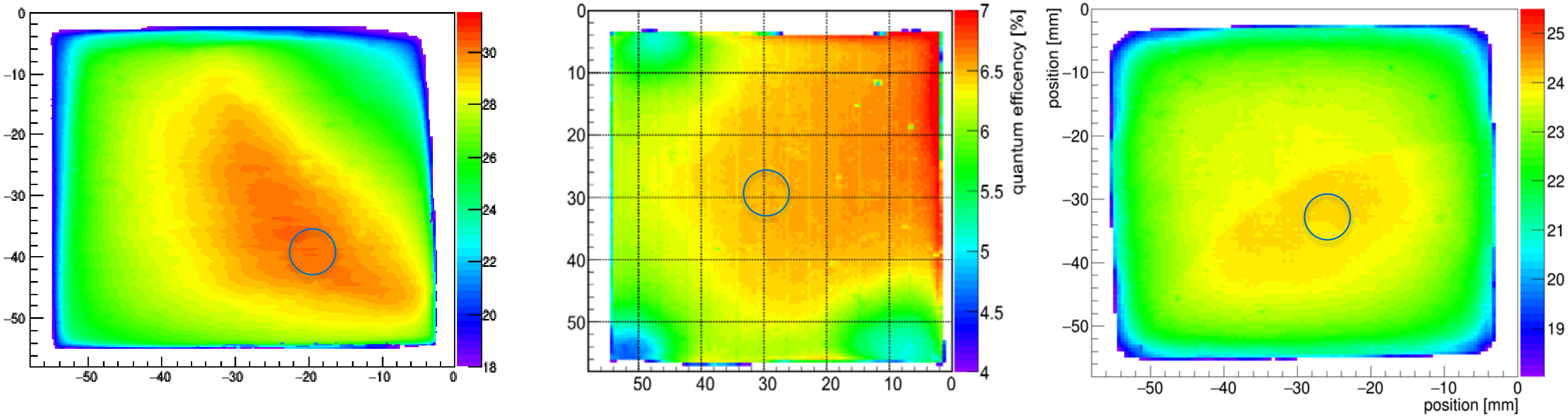




QE surface scans

- 200V at cathode, current measured at MCP-In, calculated in reference to photo diode current (known QE for wavelength)
- Scanned with 372 nm (blue) in 0.5 mm steps across surface
- Latest Hamamatsu and Photonis tubes reach ≥ 30% peak QE

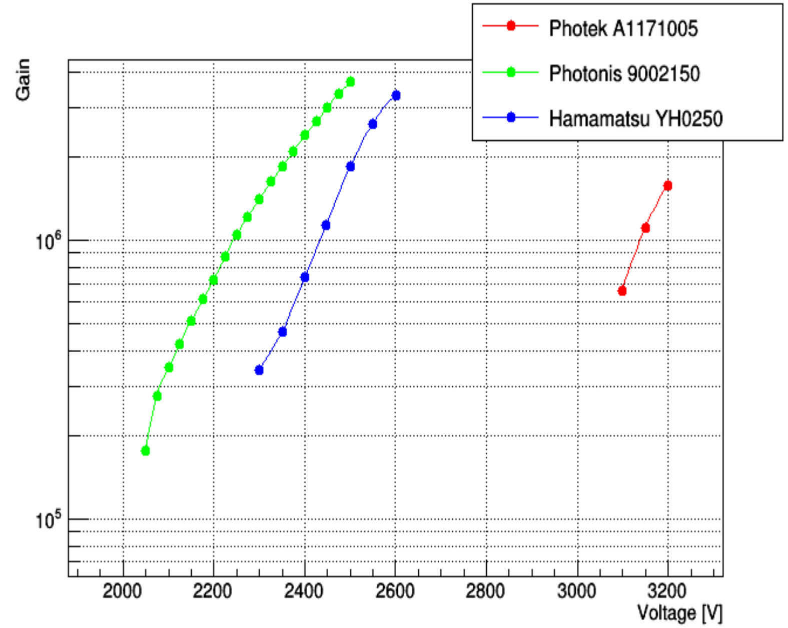


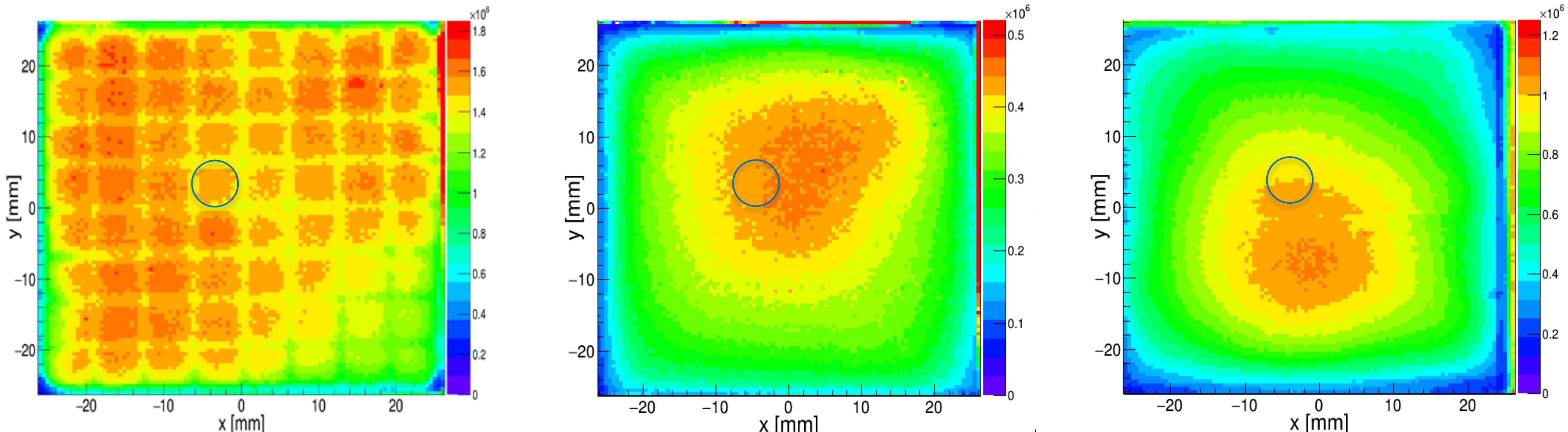


Mind the different scales

Gain measurements

- Measured with shortened anode current
- Scan data are folded with QE of the sensor
  - Have to be divided by QE
  - Scaled with point of known gain
- QE corrected gain shown in pictures below
- All tubes reach 1e6 gain, but the Photek tube needs much higher voltage



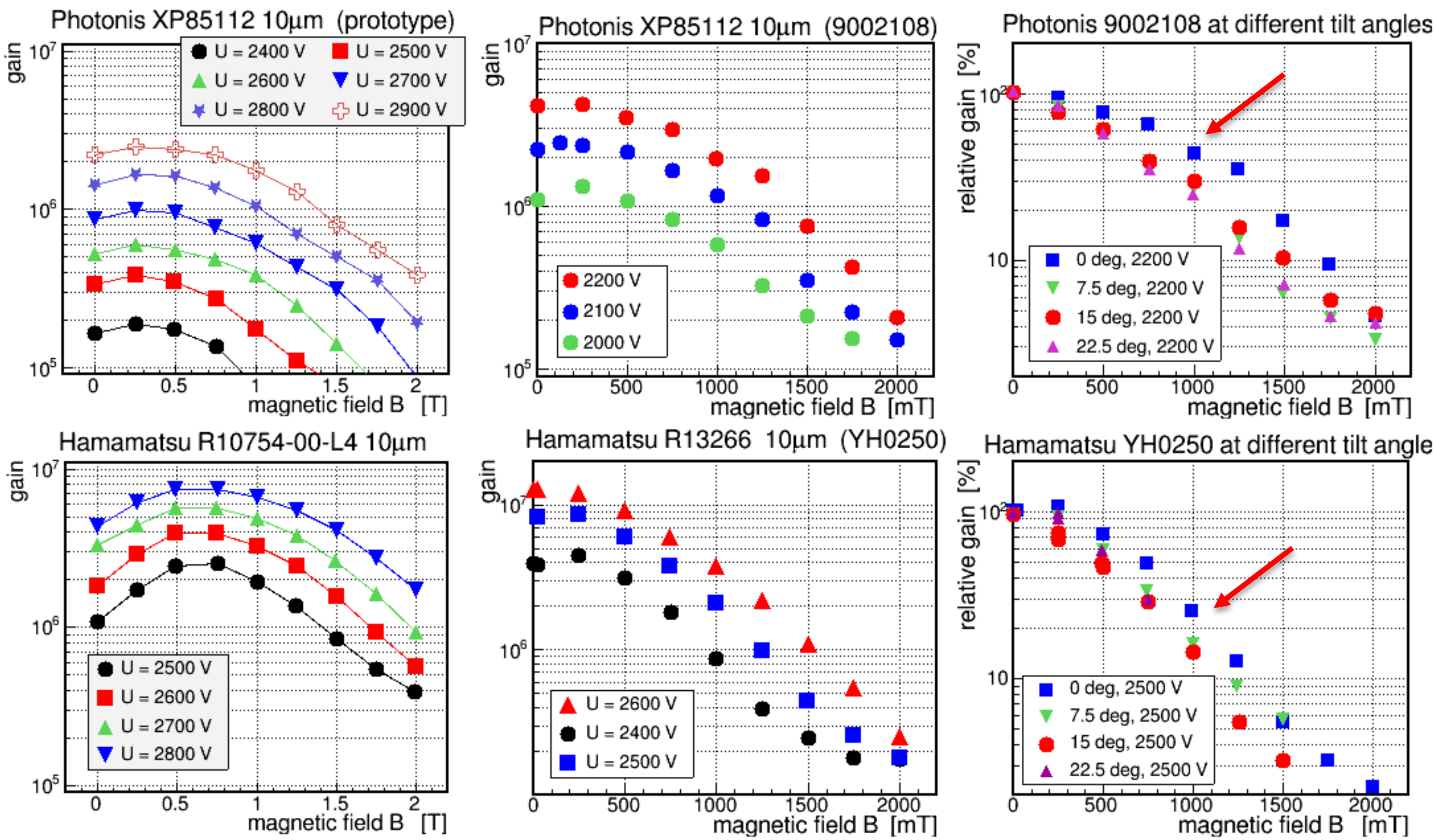


Gain of non-ALD and ALD tubes in B-field

Non-ALD | ALD, diff. HV | ALD, diff. tilt angle

Photonis

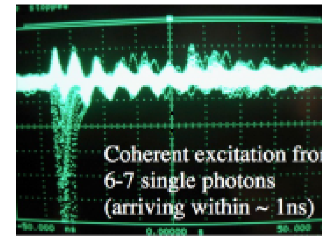
Hamamatsu



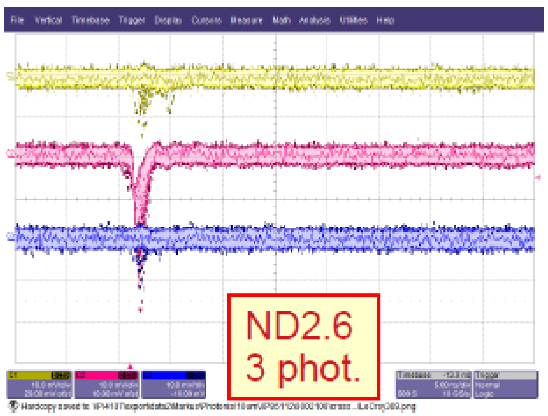
- ALD tubes show faster gain drop in B-fields than non-ALD tubes!
- **Photonis 9002108:** gain drop at **1 Tesla**, 0 deg: factor 2; **15 deg: factor 3**
- **Hamamatsu YH0250:** gain drop at **1 Tesla**, 0 deg: factor 4; **15 deg: factor 6**

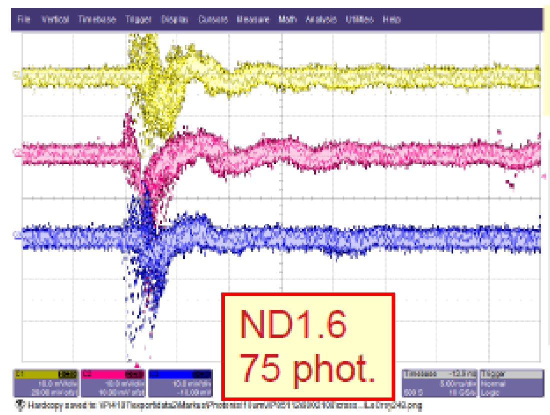
Problem: Signal Oscillations

RICH 2016: J. Vav'ra, NIM A876 (2017) 185



- J. Vav'ra: "coherent excitations" in old (2005) Planacon tubes
- Recently tested with latest MCP-PMTs:
- ALD coating; 1e6 gain; diffuse illumination of full PC area





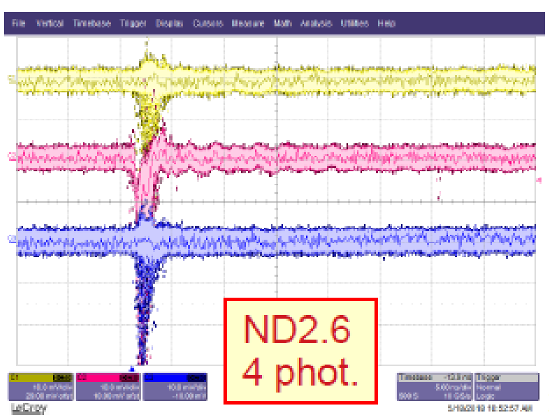
Photonis 9002108

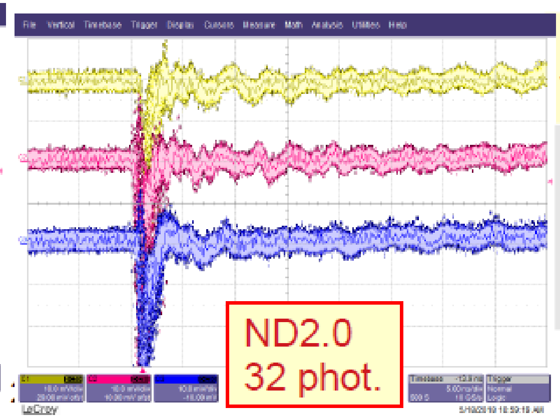
x: 5 ns/div
y: 10 mV/div

Trigger:
Laser * px44

pixel's read out

11	12	13	14	15	16	17	18
21	22	23	24	25	26	27	28
31	32	33	34	35	36	37	38
41	42	43	44	45	46	47	48
51	52	53	54	55	56	57	58
61	62	63	64	65	66	67	68
71	72	73	74	75	76	77	78
81	82	83	84	85	86	87	88



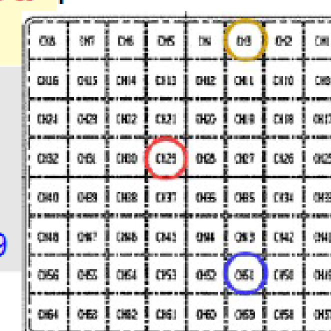


Hamamatsu YH0250

x: 5 ns/div
y: 10 mV/div

Trigger:
Laser * CH29

pixel's read out

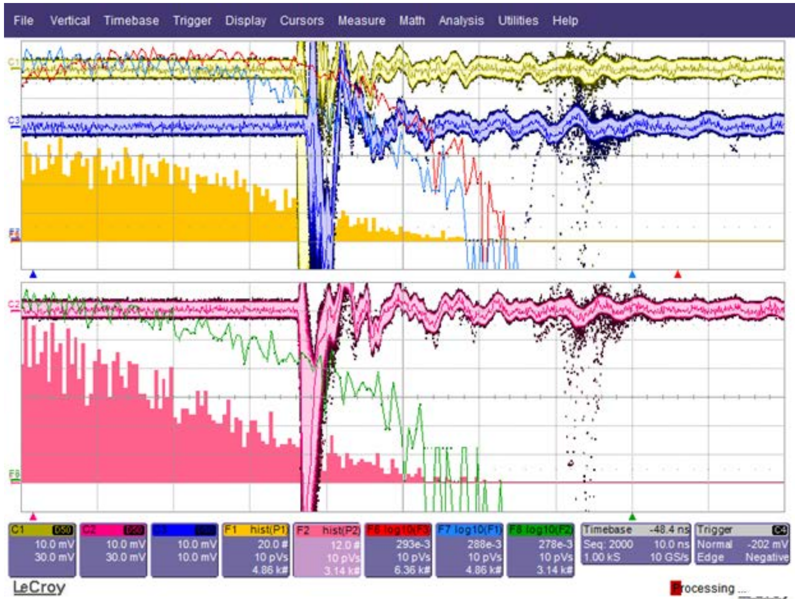


Photonis 9002108 and 9002150

- Tested Tubes: Photonis 9002108 and 2150, which has a new backplane
- Noticable less ringing, also on covered Pixels (yellow trace)
- Red (632 nm) PiLas, 10 kHz, illumination of full sensor
- ALD coating, 1e6 gain

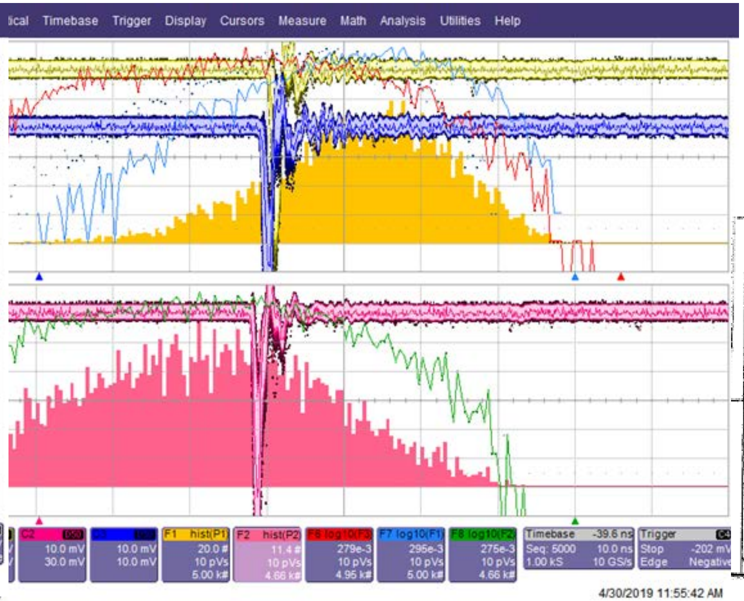
x: 10ns/div
y: 10mV/div

Trigger:
Laser pulse



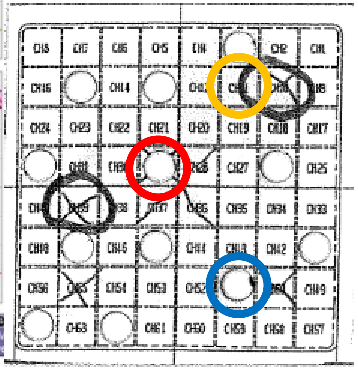
9002108

64 Pixels * 7 Photons/Pulse = 450 Photons



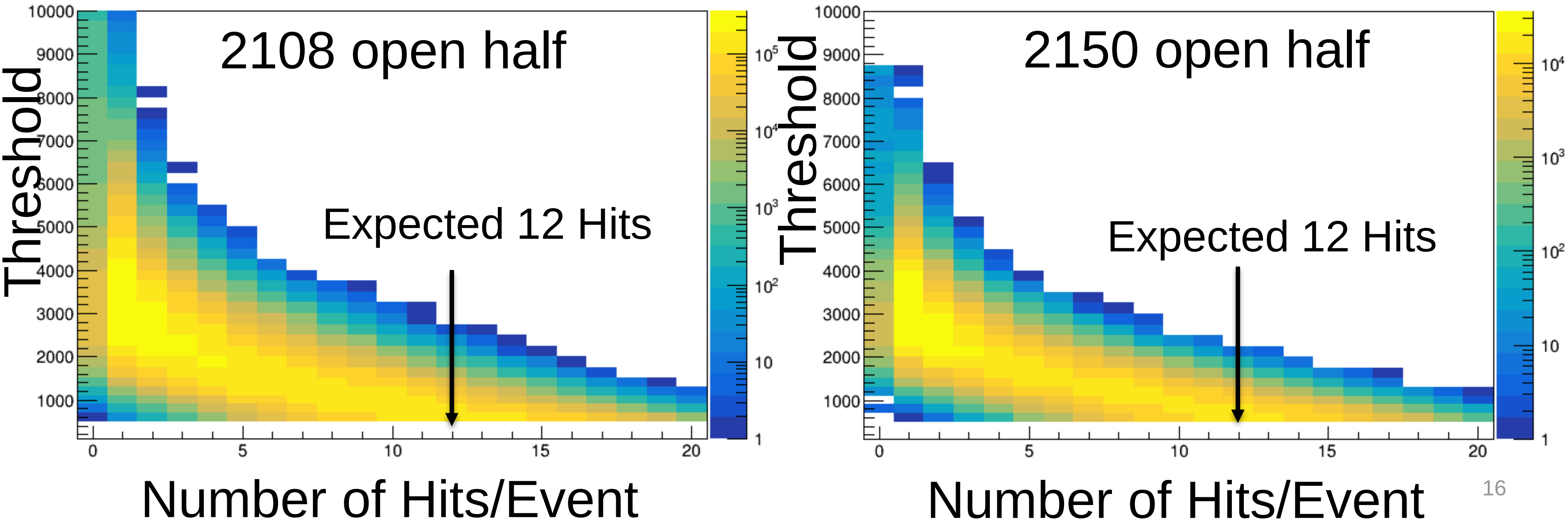
9002150

64 Pixels * 7 Photons/Pulse = 450 Photons



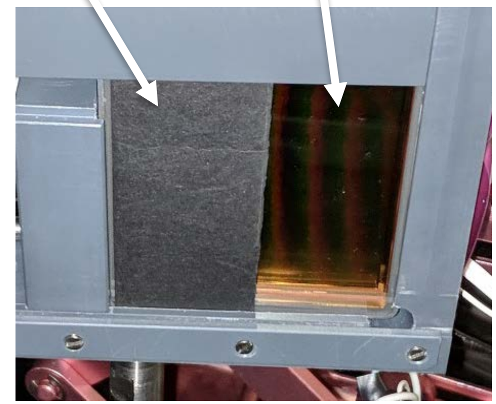
Crosstalk behavior using TRB DAQ

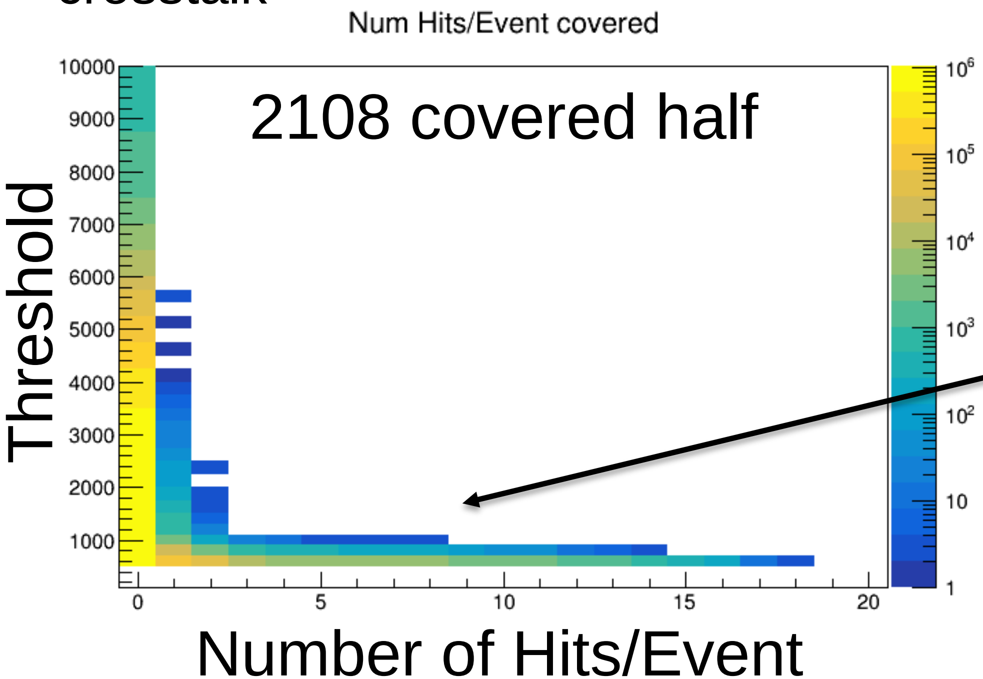
- Cover half of the MCP-PMT and read out only the 3 most left and right rows
- Look at the number of simultaneous hits in a 15 ns window around the laser peak on the covered and open side at different thresholds
- Adjust ND-Filter to get ~1 p.e./Pixel ($\bar{n}_{pe}$), adjust the voltage to get the same signal height distribution in both MCP-PMTs
- Illuminated half: ~12 hits expected [24 pixels * (1- exp(-$\bar{n}_{pe}$) with $\bar{n}_{pe} \sim 0.7$]
  Covered half: only crosstalk ("fake") hits from oscillation should be seen

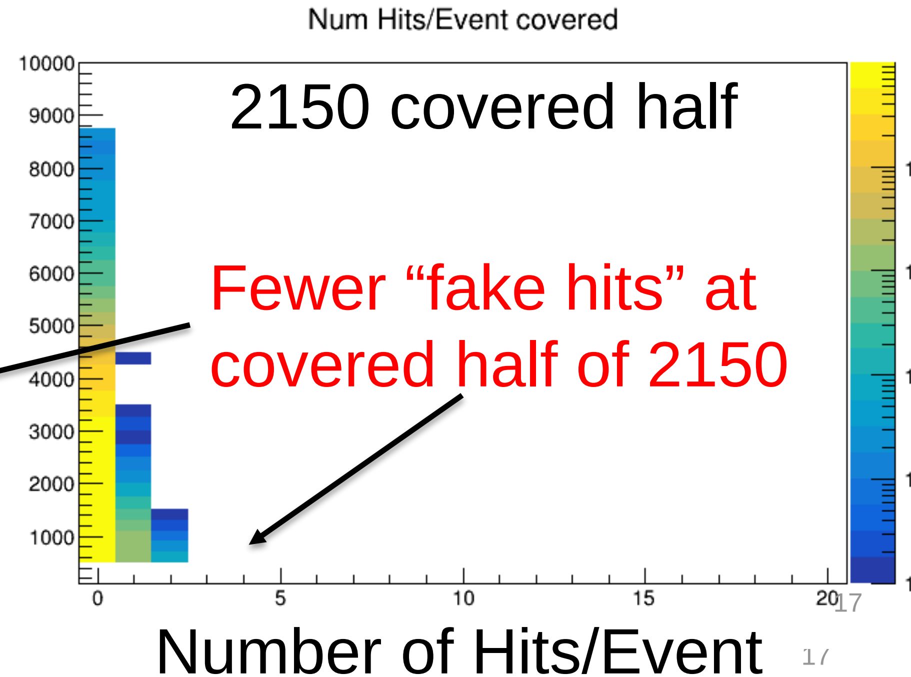


Crosstalk behavior using TRB DAQ

- 9002108: at low threshold crosstalk events with up to 18 Hits/Laser pulse can be observed
  9002150: only up to 2 Hits/Laser pulse seen
- Crosstalk signal height also 25% smaller on 2150 compared to 2108
- Photonis PMT with new backplane reduces ringing and crosstalk

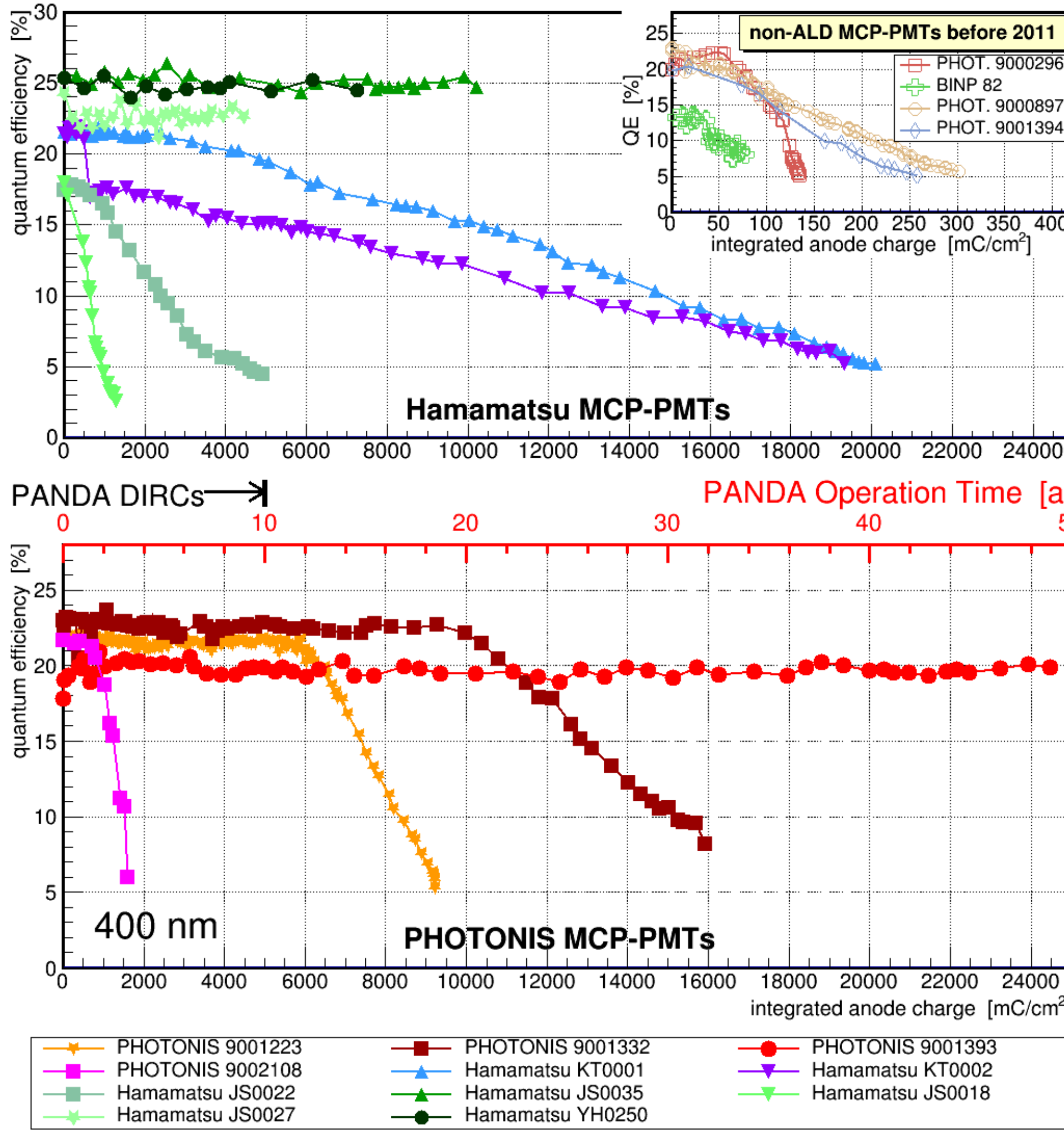






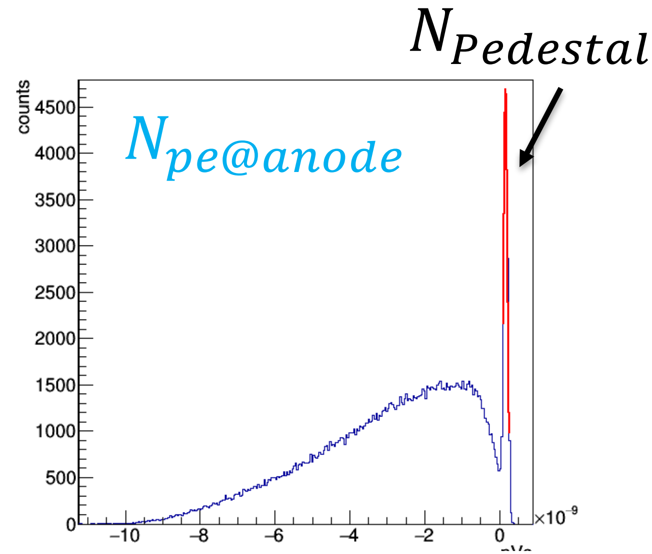
Most recent Lifetime measurement results

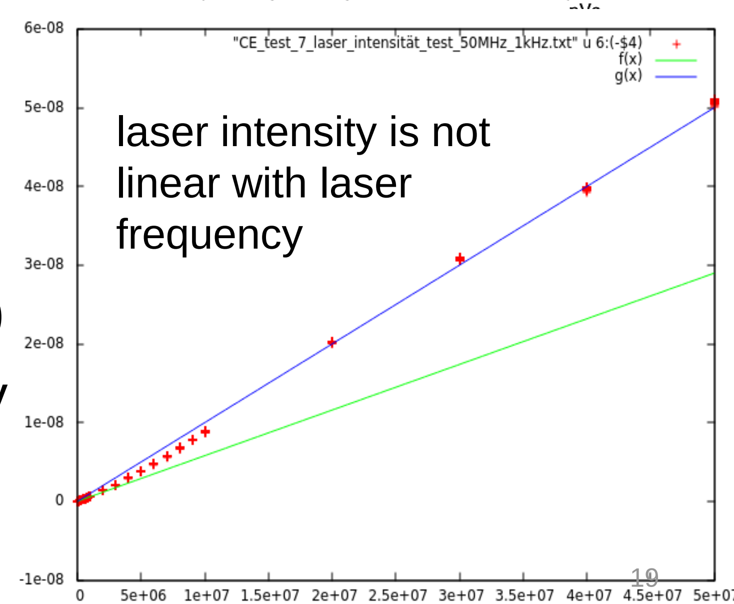
- Requirements: > 5 C/cm² at 1e6 gain (50% duty cycle, 10 years)
- Lifetime of < 200mC/cm² for tubes without countermeasures
- Lifetime increased by a factor of 50-100 with ALD coating
- Both Hamamatsu and Photonis tubes have reached > 5 C/cm²
- We didn't measure the lifetime of any Photek tube until now



Idea of collection efficiency (CE) measurement

- Idea: $\mathrm{CE} = N_{pe@anode@15kHz}$ / $N_{pe@PC@15kHz}$
- $N_{pe@anode}$: Poisson statistics of charge spectrum (with a Picosecond Laser (PiLas) at 15 kHz and a nd-filter)
- $N_{pe@anode@15kHz} = -\ln(N_{Pedestal}/N_{all})$
- $N_{pe@PC@15kHz}$ is difficult to determine
- Direct measurement via illumination of a certain area with a PiLas and current measurement at PC or first MCP (like quantum efficiency)
- $N_{pe@PC@15kHz} = \frac{I_{pe@PC@15kHz}}{e \cdot 15kHz}$ is really low (~fA)
- Increase laser frequency to 50 MHz, $I_{pe@PC@50MHz}$ still low, but measureable (~10pA)
- Laser is not linear -> monitoring of light intensity needed





Idea of collection efficiency (CE) measurement

- Monitoring of light intensity with a photodiode
- Introduction of correction factor F to compensate non-linearity
- $F = \frac{I_{Diode@50MHz}}{I_{Diode}@15kHz} \frac{15kHz}{50MHz}$
- Use of QE-Setup (200V between PC and MCP and current measurement) with a beam splitter
- Beam to sensor goes through nd-filter (1-2 photoelectrons per pulse)
- Beam to diode is unattenuated
- $N_{pe@PC@15kHz} = \frac{I_{PC@50MHz}}{50MHz \cdot e} / F$
- $\mathrm{CE} = \frac{N_{pe@anode@15kHz} \cdot e \cdot 15kHz}{I_{PC@50MHz}} \frac{I_{Diode@50MHz}}{I_{Diode@15kHz}}$

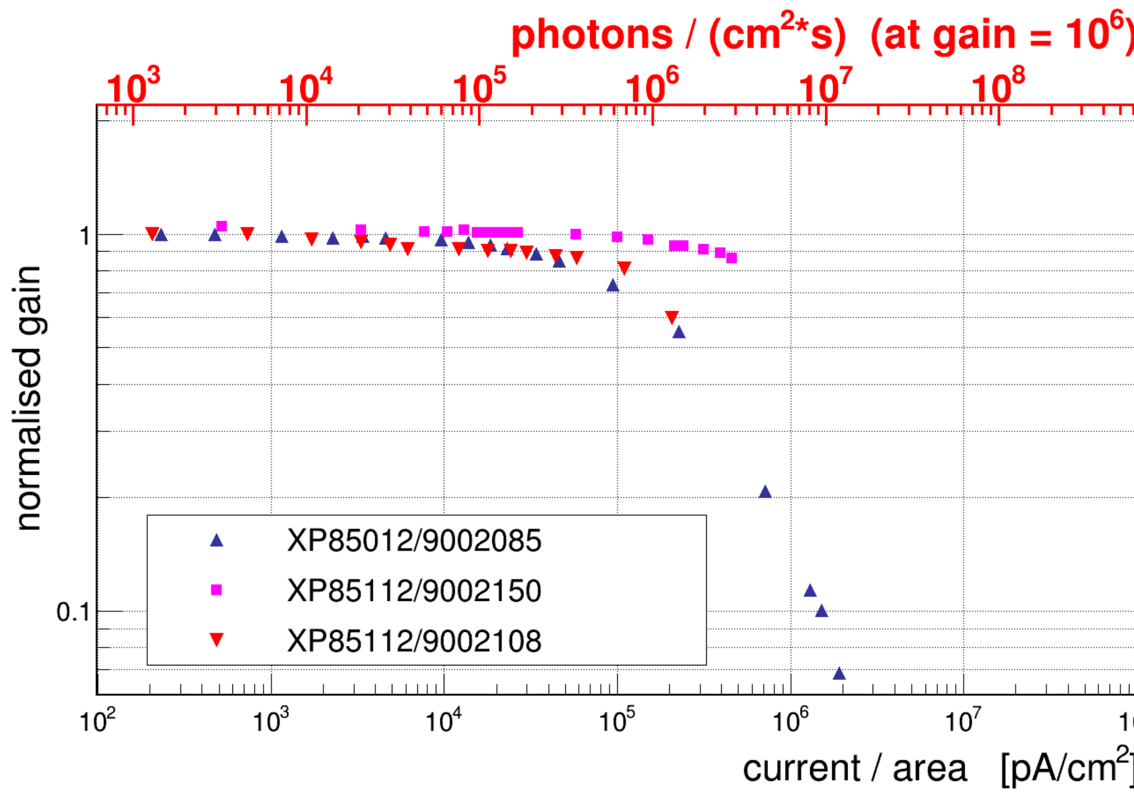
Results of collection efficiency (CE) measurement

	Photonis XP85112 9001394	Photonis XP85112 9002108	Hamamatu R13266-07 JS0022	Photek MAPMT253 A1171005	Hamamatsu R10754X-07 KT0001
comments	non-ALD, no film	ALD, Hi-CE no film	ALD, film before MCP	no film	ALD, film between MCPs
CE	(63 ± 6)%	(95 ± 9)%	(39 ± 4)%	(83 ± 8)%	(76 ± 8)%

- ~60% for Photonis 9001394 seems reasonable
- Photonis 9002108 is higher (Hi-CE), Hamamatsu JS0022 is lower (protection film through which electrons have to pass)
- errors are estimated to be at around 10% level
- -> high DQE (= CE * QE) (up to 30%) for Hi-CE tubes

Rate stability

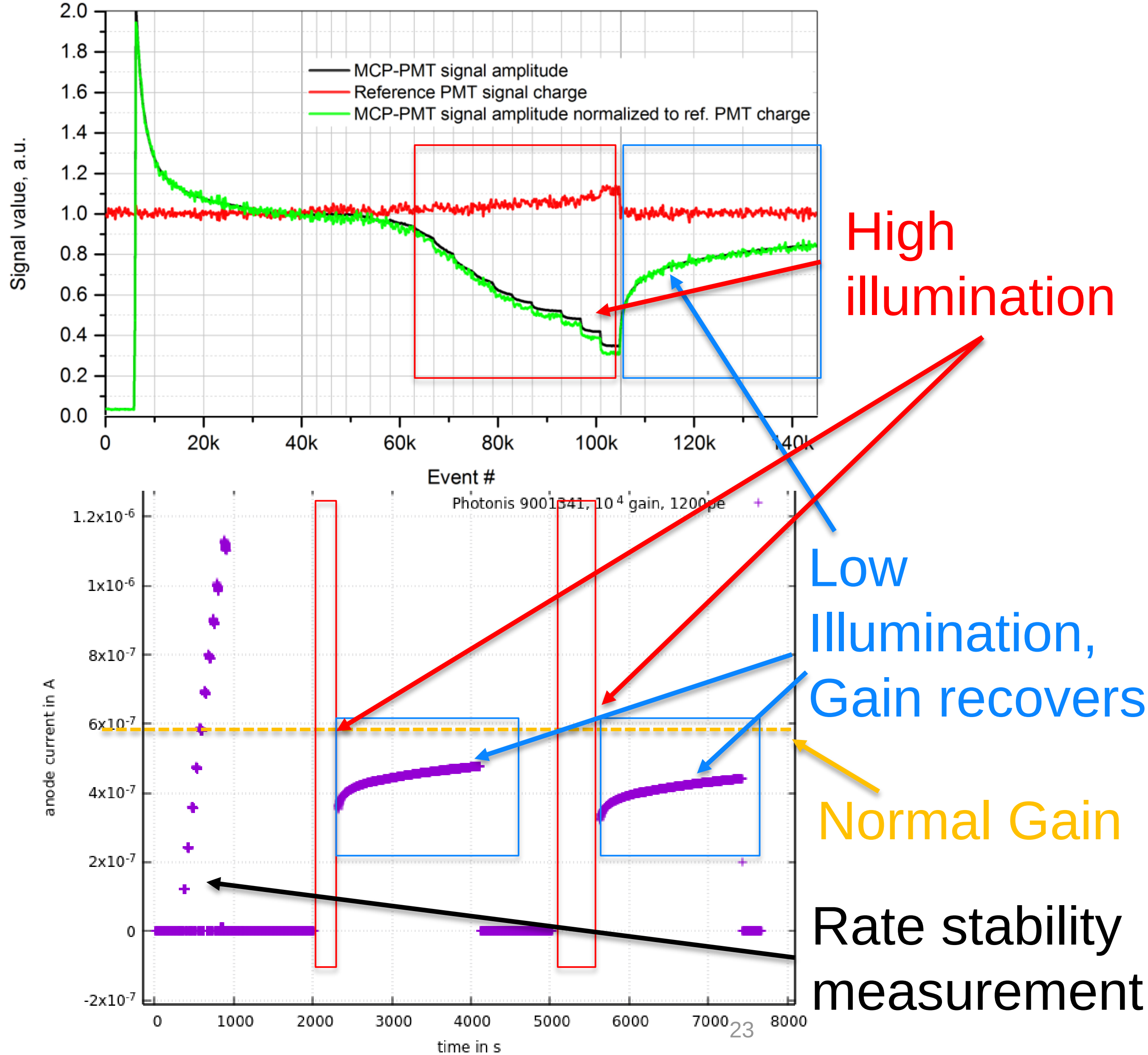
- Measured with shortened anodes at $\sim 1 * 10^6$ gain
- Fully illuminated sensor and photodiode in same light spot (diffuser)
- Monitor diode and shortened anode current for different laser frequencies
- In theory, when diode current doubles anode current should double too
- Normalize to first value taken:
- $y = \frac{Anodecurr\_x}{Diodecurr\_x} / \frac{Anodecurr\_1}{Diodecurr\_1}$



- Normalized gain should be 1 if sensor doesn’t change its gain
- Higher rates were not accessible because of limitation of anode current

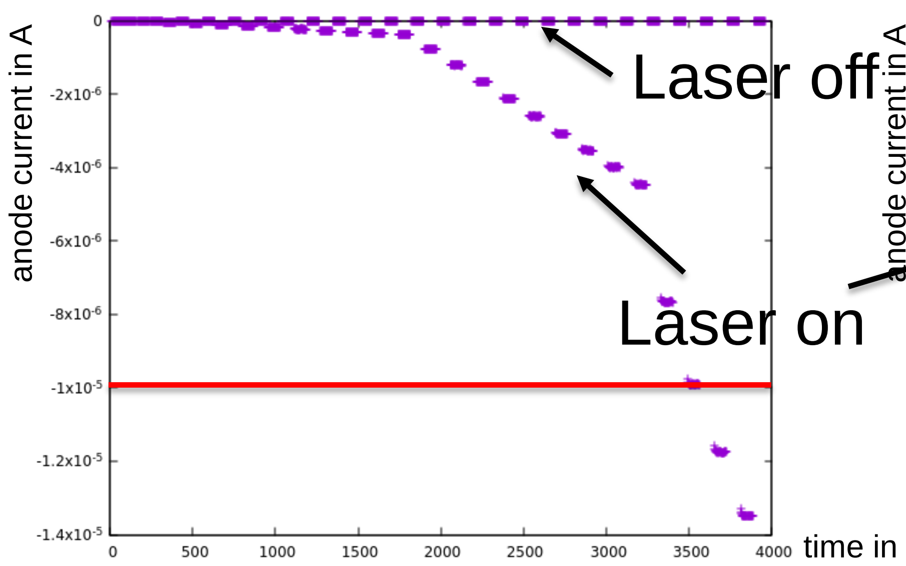
Gain recovery

- Antamanova et al. observed (2018 JINST 13 T09001)
  - After high illumination the gain is lower than before
  - Only in ALD tubes, but not in non-ALD tubes
- We can reproduce this effect
- This effect is under further investigation

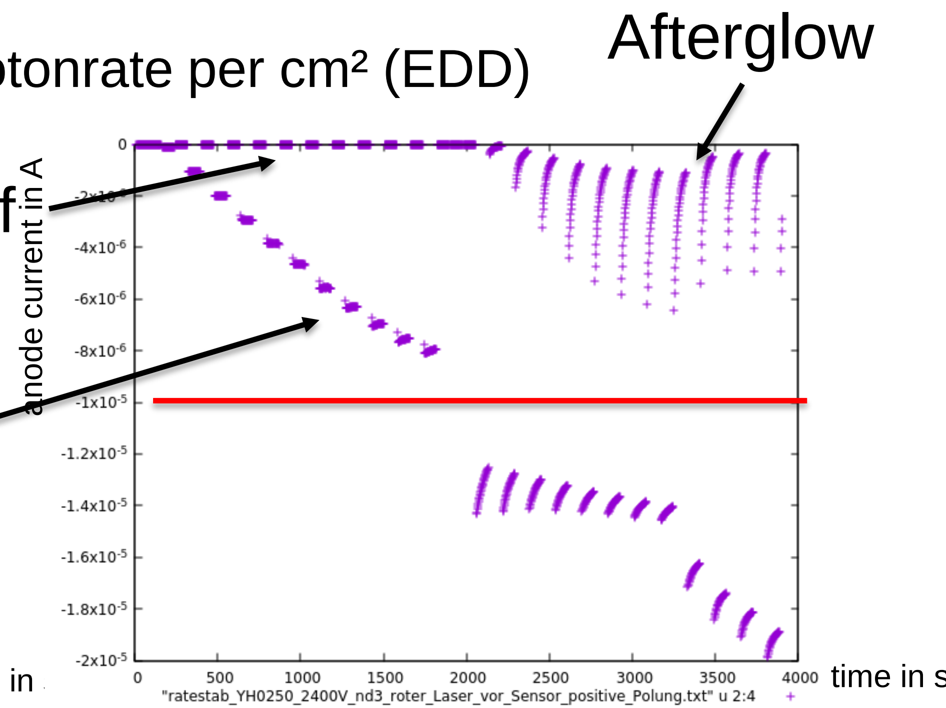


Saturation and Afterglow

- After illuminating MCP-PMTs with high intensity light the darkcount rate is significantly increased
- The count rate decays within several seconds - minutes
- This effect can also be observed during our rate stability measurements:
- Red line corresponds to 2MHz photonrate per cm² (EDD)



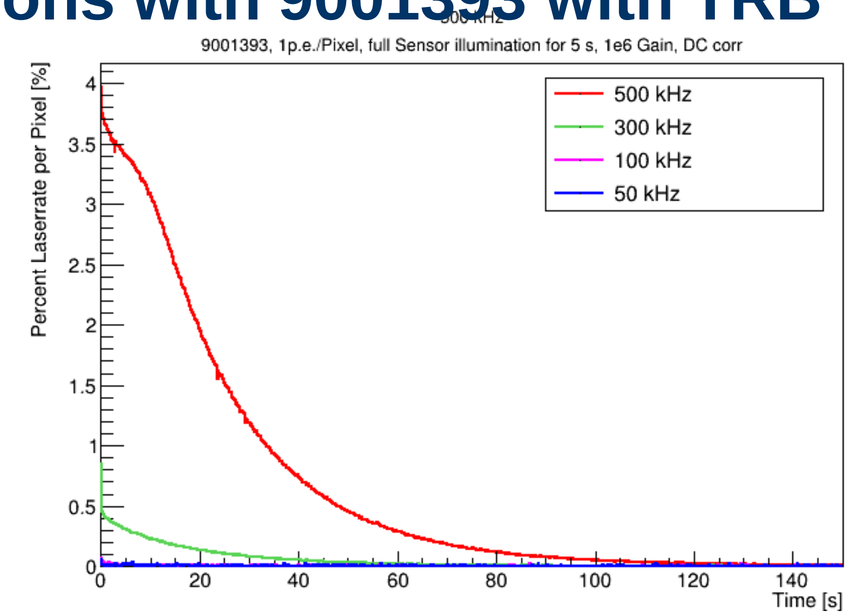
Photonis 9001393-URD

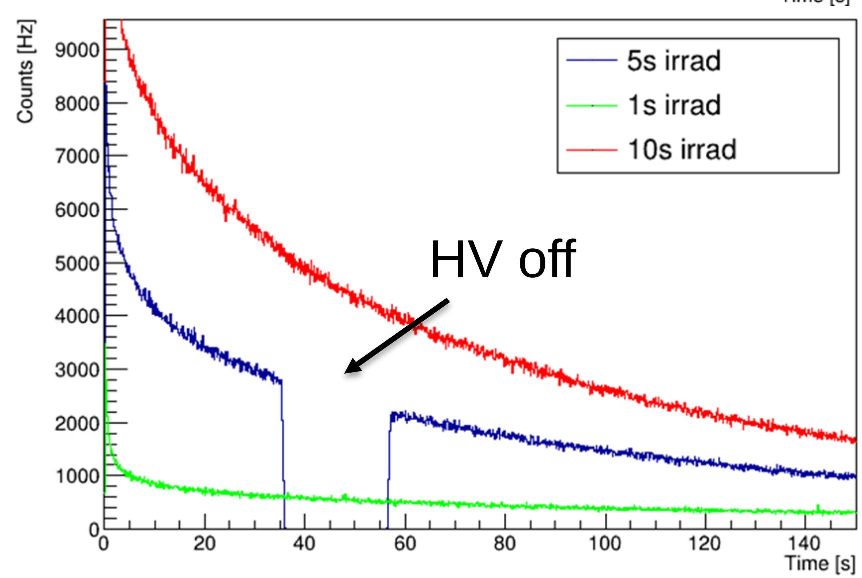


Hamamatsu YH0250

Afterglowing – further investigations with 9001393 with TRB

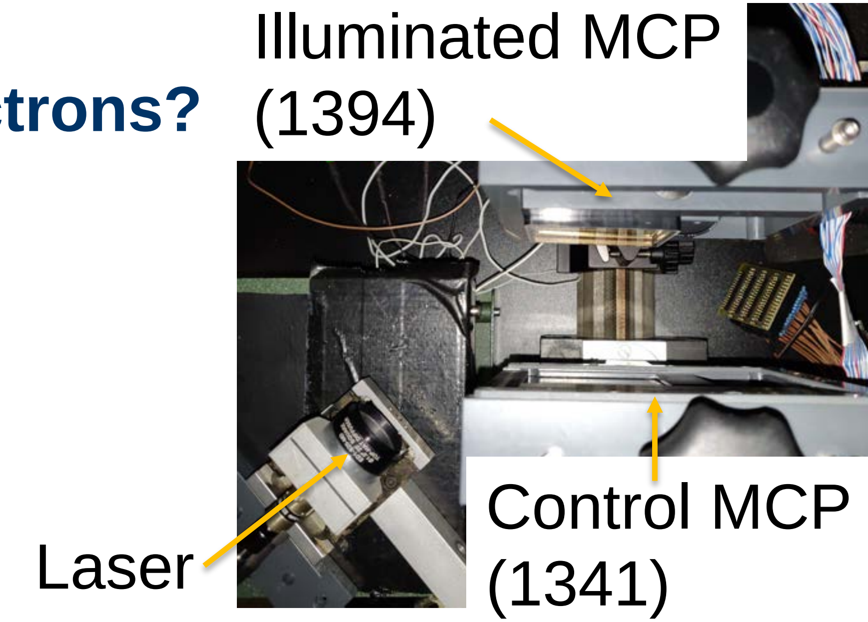
- Illuminating the full MCP-PMT PC several seconds with ~1 p.e./Pixel, then turn off the laser and measure the count rate for 300 s
- Higher illumination intensity (laser frequency) results in more afterglow
- Observed up to 10% afterglow events compared to the laser rate
- Longer illumination intensity results in more afterglow
- Turning off the HV during the decay has no effect on the number of afterglow events
- Amount of afterglow events depends on the voltage applied (gain) during the illumination

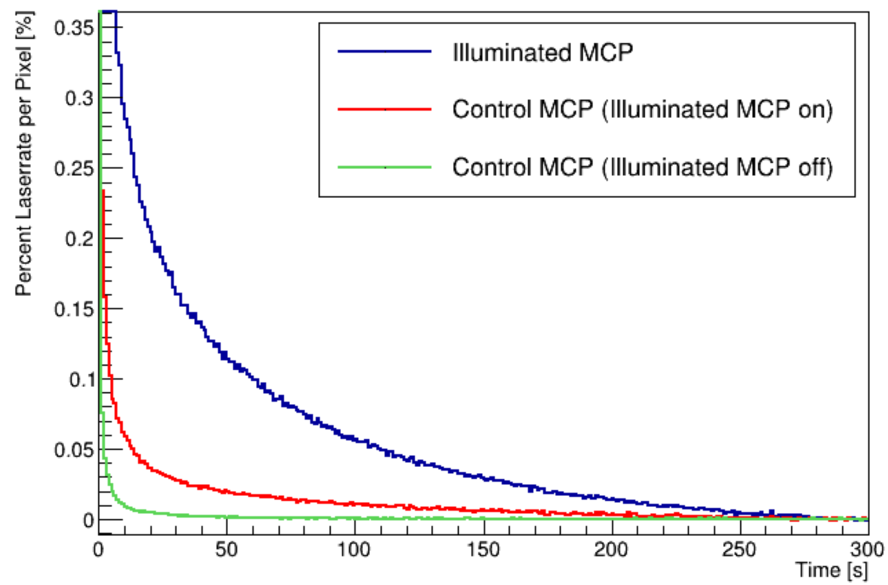




Afterglowing - photons or electrons?

- Measured two facing MCP-PMTs, once with the illuminated MCP-PMT turned on and once turned off
- Observe the count rates of the control MCP-PMT
- Count rates of the control MCP-PMT are higher when the illuminated MCP-PMT has been turned on
- ->Afterglow effect must be based on Photons





Summary

- The investigated Hamamatsu, Photek and Photonis tubes have
  - Time resolution <50 ps Sigma and <200 ps RMS
  - Very low darkcount rate of <1kHz / MCP-PMT
  - Low afterpulse probability of <1%
  - Average gain and QE homogeneity
  - QE up to 30% for Hamamatsu and Photonis tubes with high CE -> DQE up to 30%
- All tubes show ringing, but new Photonis backplane reduces it significantly
- Lifetime of Hamamatsu and Photonis ALD-coated tubes > 5 C/cm² (best at 25 C/cm²), but no Photek tube measured yet
- ALD tubes show strange saturation, recovery and afterglow effects
  - Needs to be investigated further
- Latest MCP-PMTs suitable for PANDA DIRCs