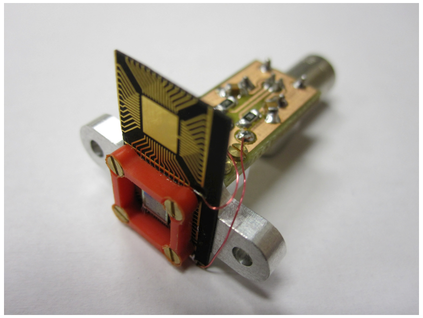
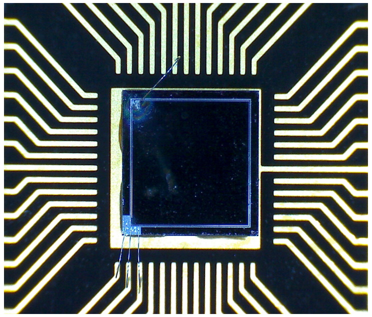
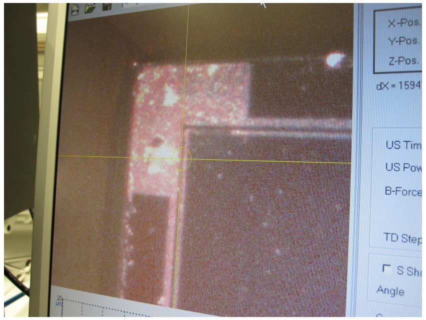
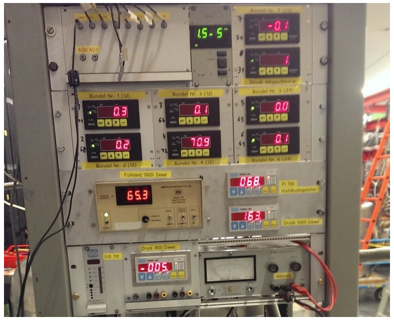








Study of Solid-state Photo-detector Properties at Cryogenic Temperatures

- Maik Biroth, Patrick Achenbach, Evie Downie, Andreas Thomas
  Institut für Kernphysik, Mainz, Germany

NDIP 2014 in Tours

A2

Crystal Ball Collaboration

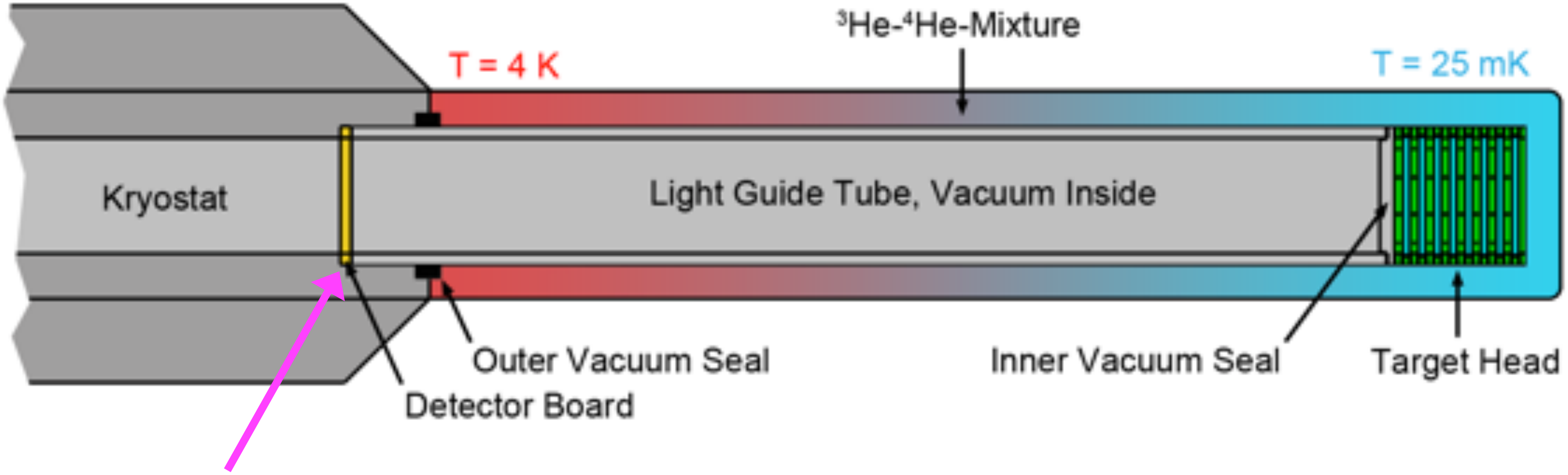
mami
MAINZER MIKROTRON

SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

JG|U
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Motivation for SiPM
@ Cryogenic Temperatures T < -200°C

A fast optical detector operating at cryogenic temperatures
is required for a nuclear physics scattering experiment

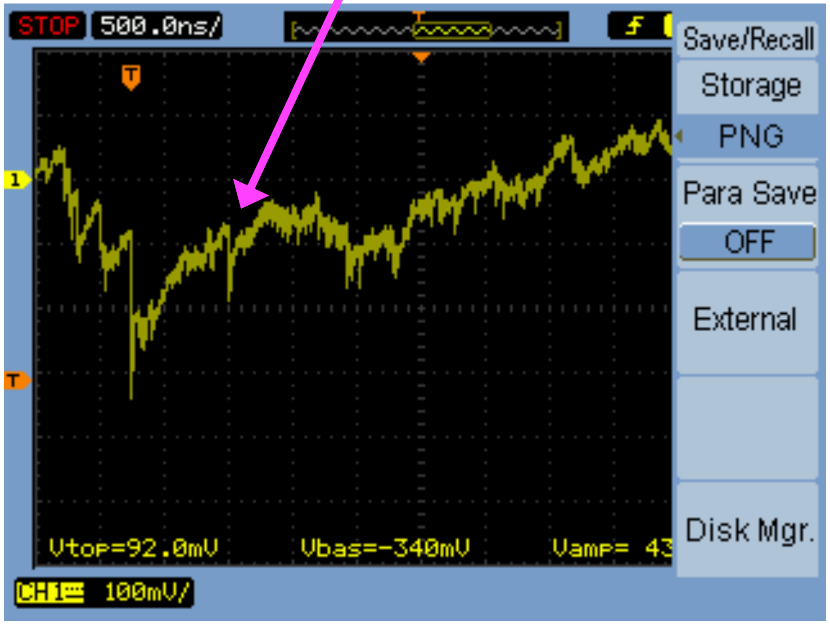


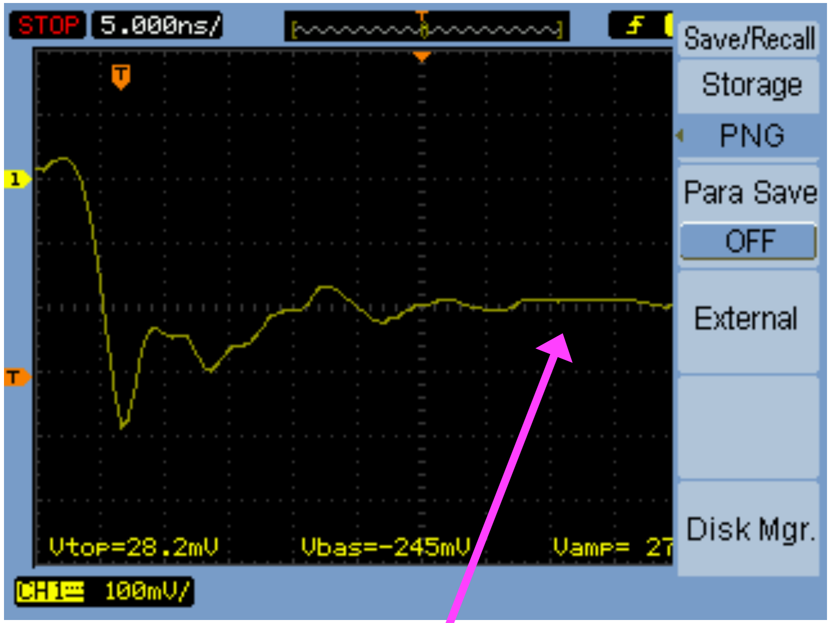
SiPMs @ T = 4K

→ Cryogenic tests of SiPMs

SiPMs @ Cryogenic Temperatures

Charge carrier freeze-out below 100K
➔ Increase of after-pulse probability because of trapping[1]





Passive quenching failed @ 77 K
➔ Current flows for microseconds
(Hamamatsu S10362-11[2])

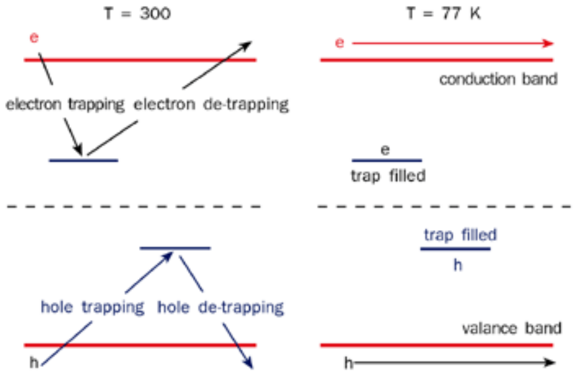
[1] G. Collazuol et al. Studies of silicon photomultipliers at cryogenic temperatures. Nucl. Instrum. and Meth. A, 628:389–392, 2011

[2] MPPC S10362-11 Technical Datasheet. Hamamatsu Photonics, Solid State Division, Hamamatsu City, Japan, 2013

Why nevertheless try it?

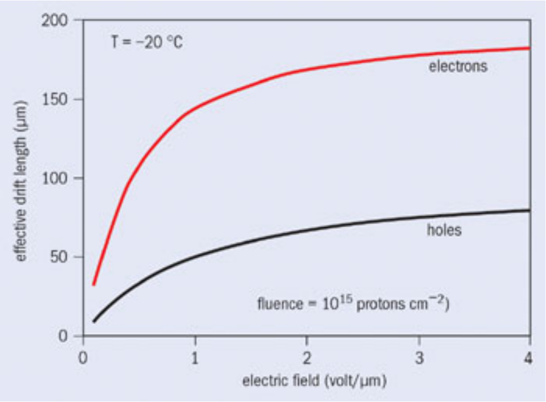
Healing of Silicon known as Lazarus effect:
Charge carrier freeze-out leads to
occupied traps with decreasing temperature
increasing relaxation time (hours till years)[7]

➔ Trapping probability decreases



Increasing charge carrier mobility with
decreasing temperature and
high electric fields leads to
increasing effective drift length[8]

➔ Trapping probability decreases

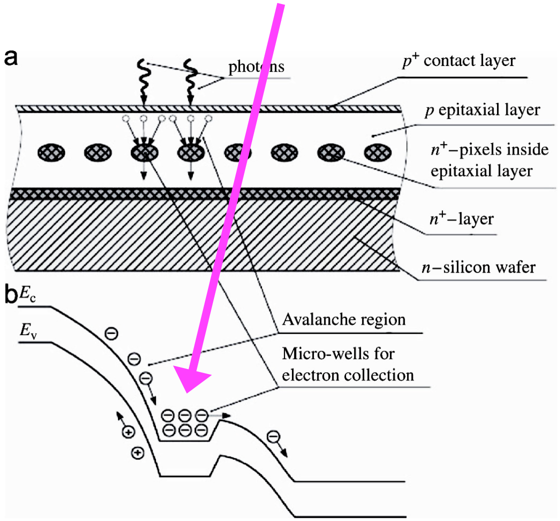


[7] Raising the dead detector, Cern Courier, 1999, Mar 28

[8] Radiation hard silicon detectors lead the way, Cern Courier, 2003, Jan 1

MAPD-3N @ T = 77K

New type of SiPM with high fill factor and quenching by potential walls[4]

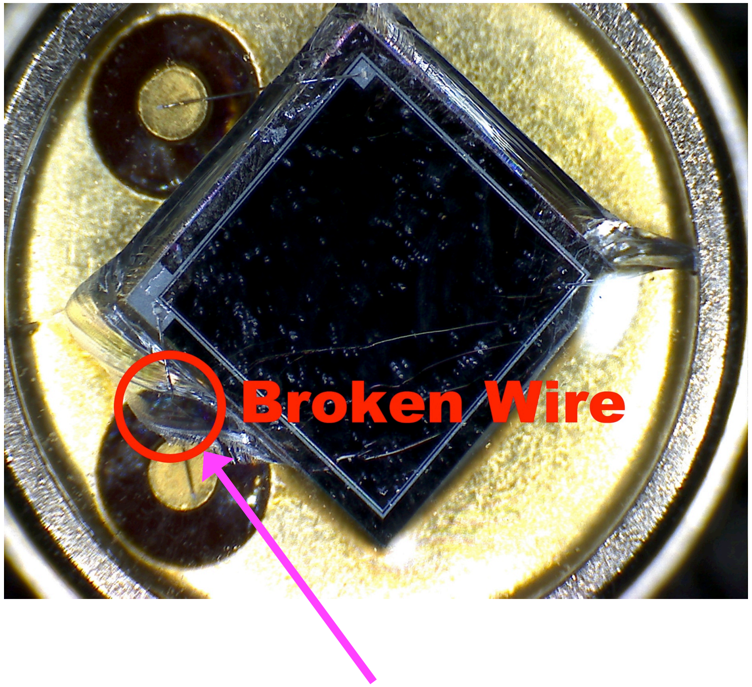


135000 pixels over 3x3mm^2

[3] *Zecotek MAPD White Paper Zecotek Photonics, Richmond, Canada, 2011*

[4] *Z. Sadygov et al. Performance of new Micro-pixel Avalanche Photodiodes from Zecotek. Nucl. Instrum. and Meth. A, 610:381–383, 2009*

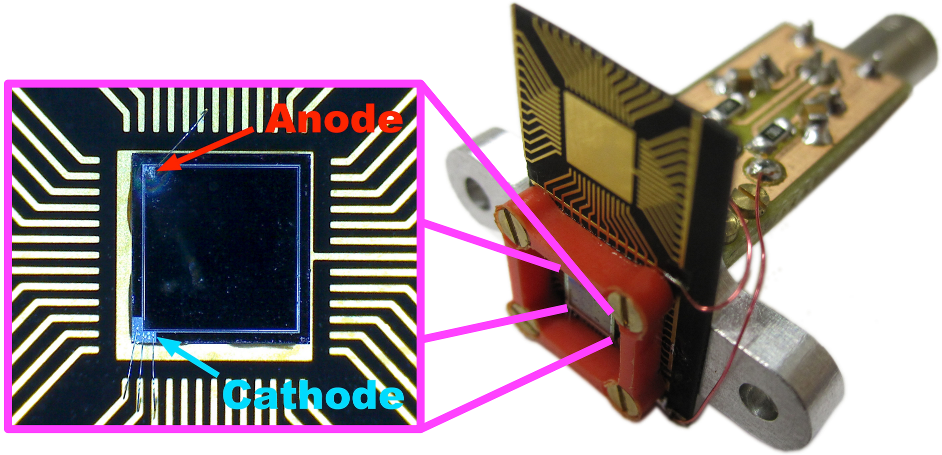
MAPD-3N[3] by Zecotek operated at liquid nitrogen temperatures

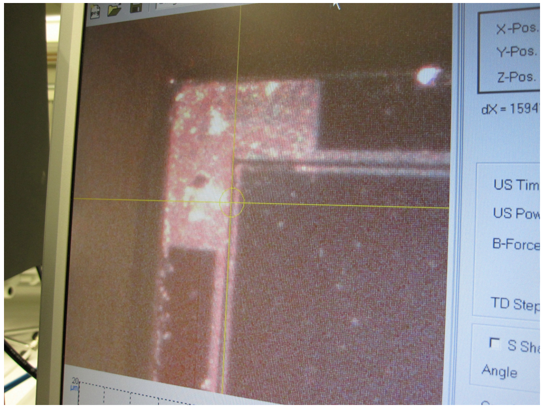


Mechanical problems after a few cycles of cooling down / heating up

Modify a Custom MAPD-3N

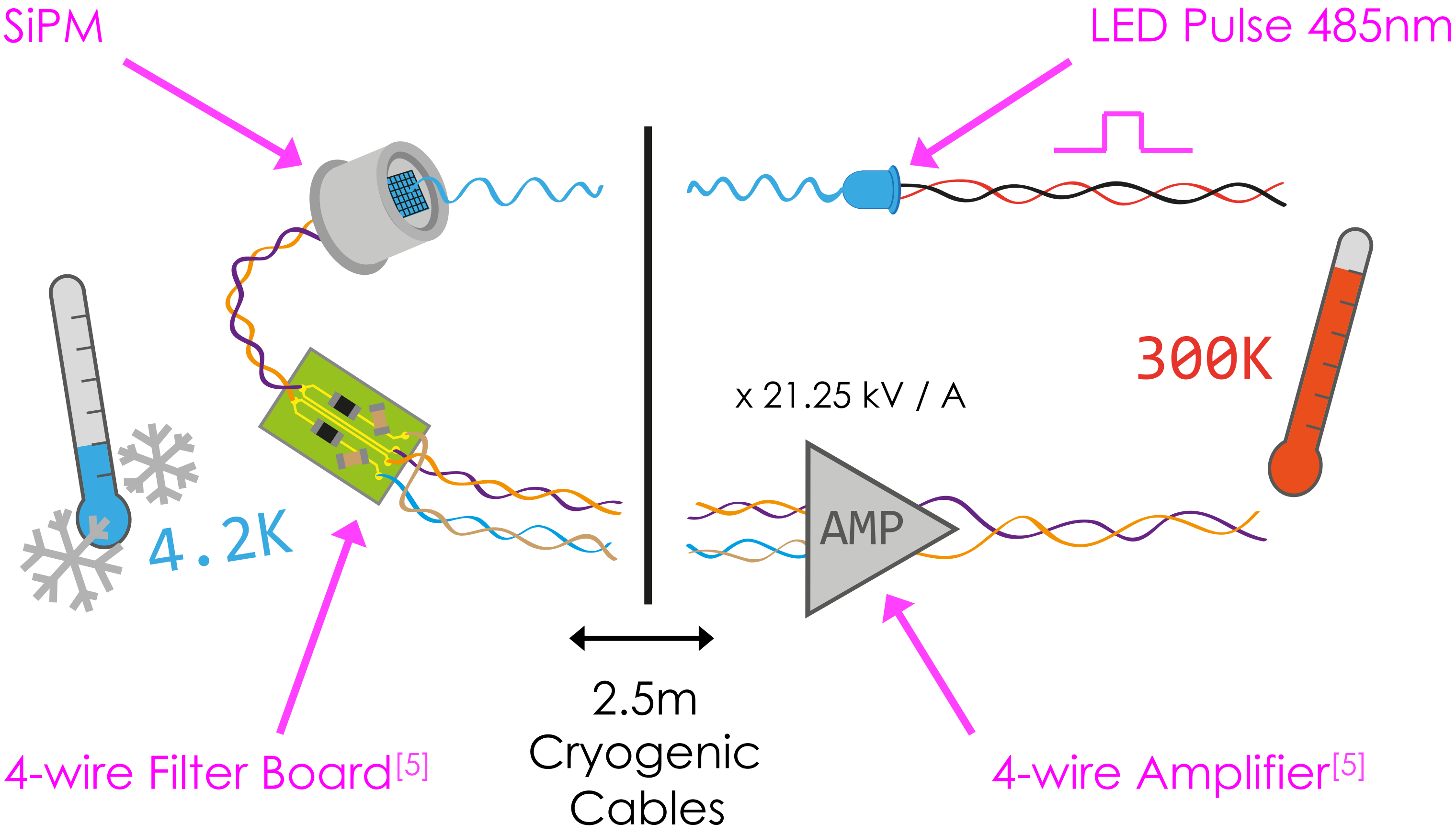
- Epoxy cover was removed with acetone and chlorinated hydrocarbons
- New bonding wire connections were made





Thanks to Harald Deppe and the hole team of CSEE Electronics, GSI, Darmstadt, Germany

Schematic Test Equipment



SiPM

LED Pulse 485nm

300K

x 21.25 kV / A

4.2K

2.5m
Cryogenic
Cables

4-wire Filter Board[5]

4-wire Amplifier[5]

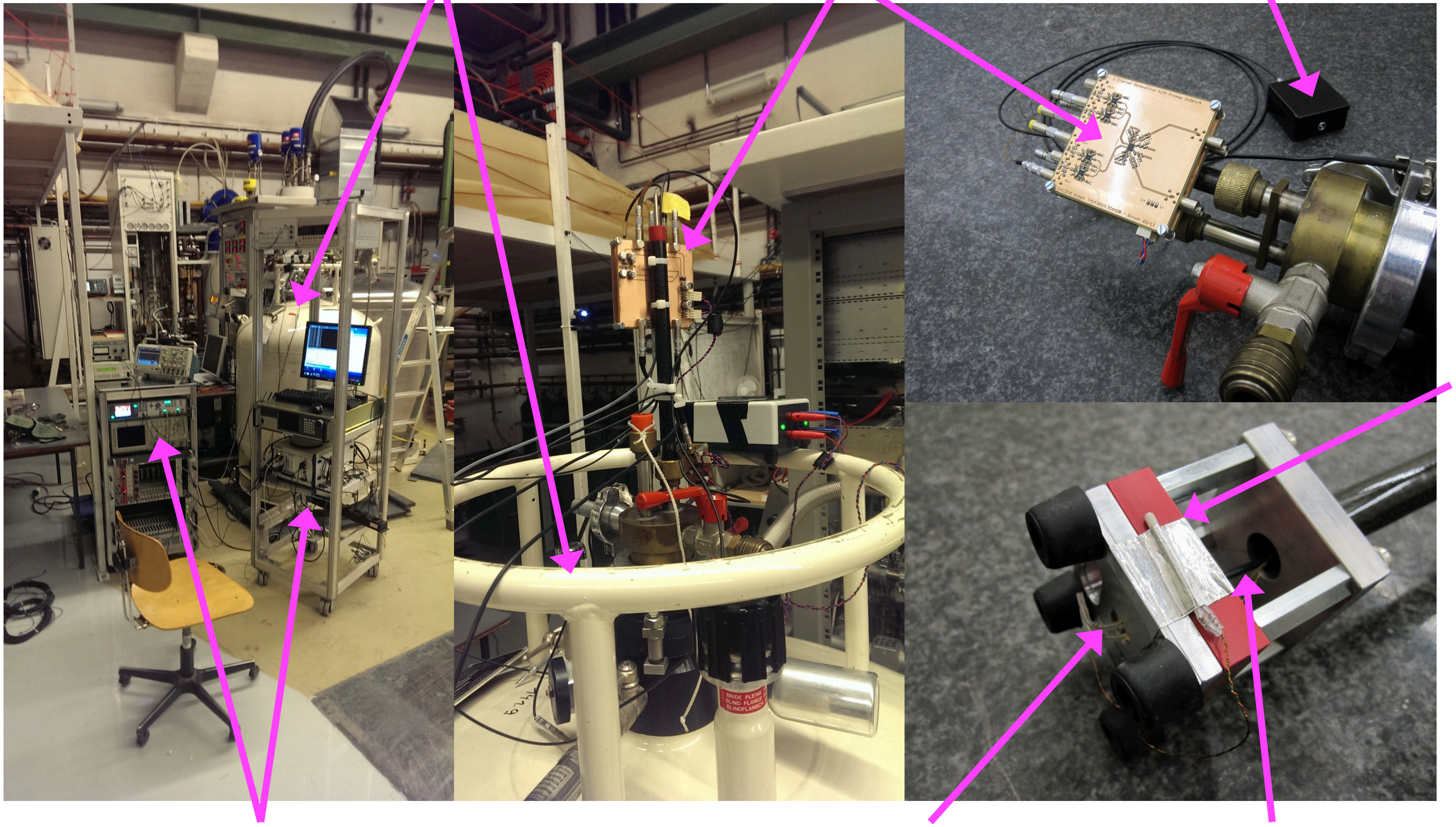
[5] Poster ID 85, A Low-noise Fast Pre-amplifier and Readout System for SiPMs

Photos of the Test Equipment

Helium Dewar

4-wire Pre-amplifier

LED Pulser + Fiber



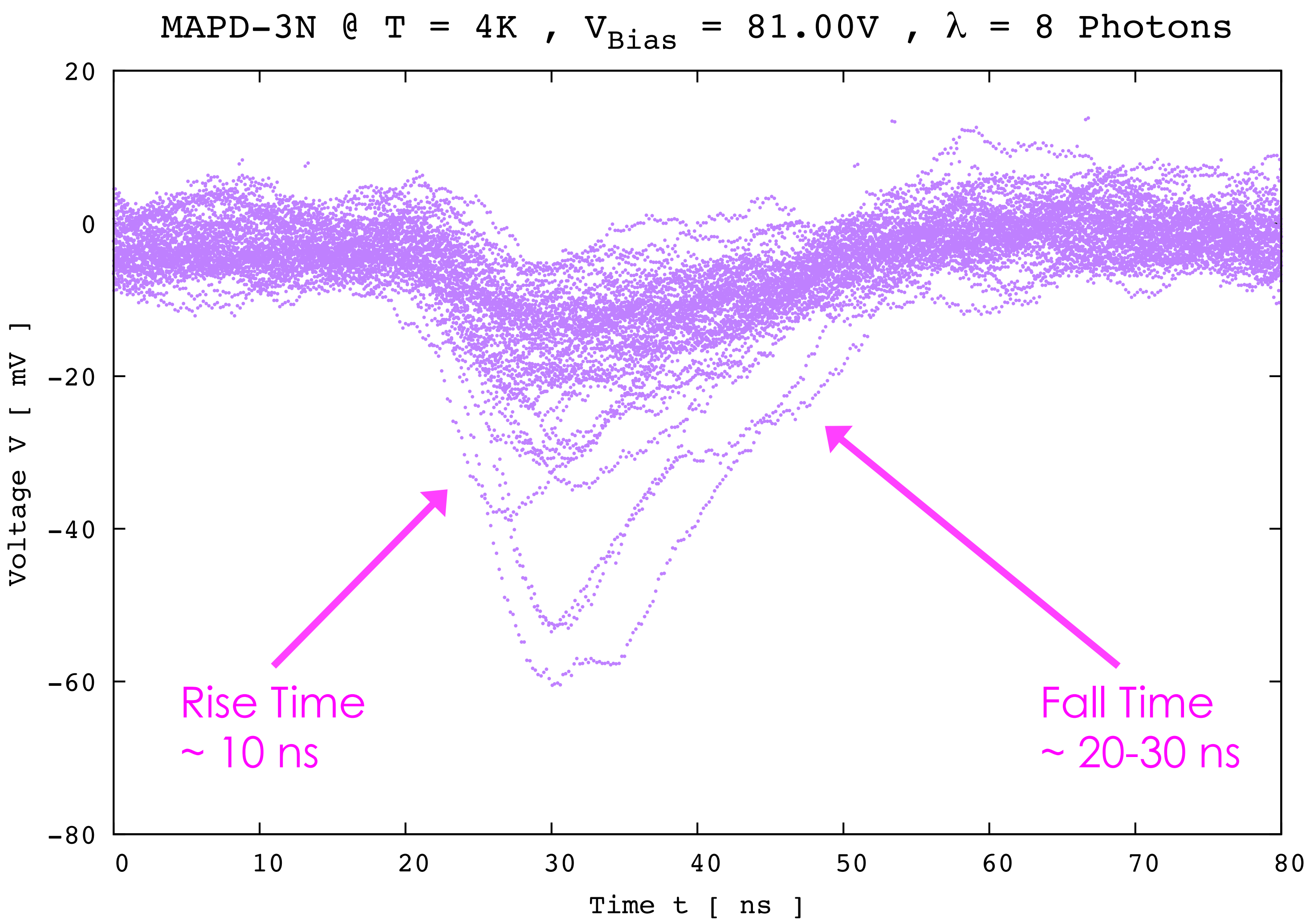
Data Acquisition Electronics

SiPM

Incoming Fiber

4-wire Temperature Probe (Platinum + Carbon)

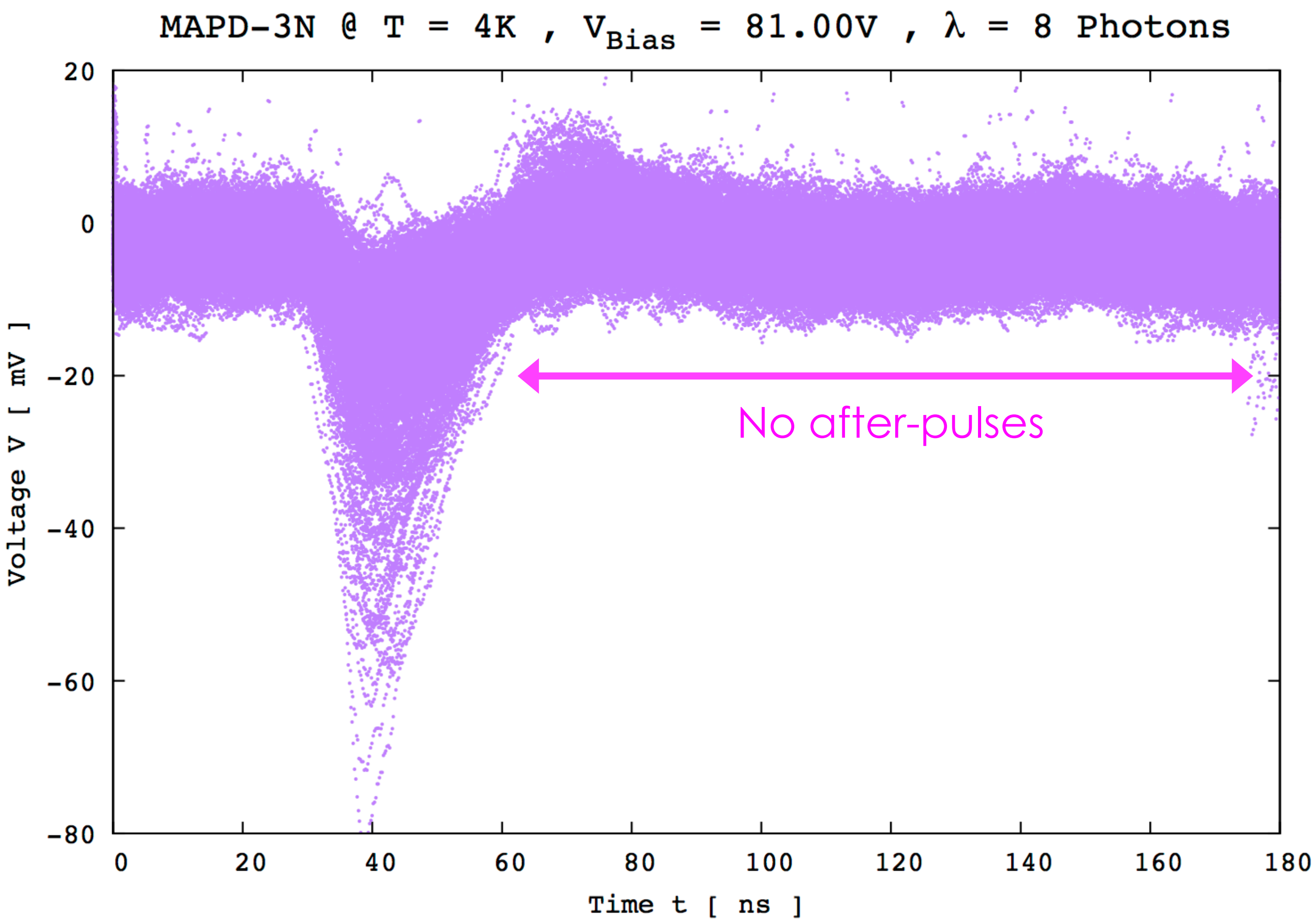
Good Signal Pulse Shape @ T = 4K



Rise Time
~ 10 ns

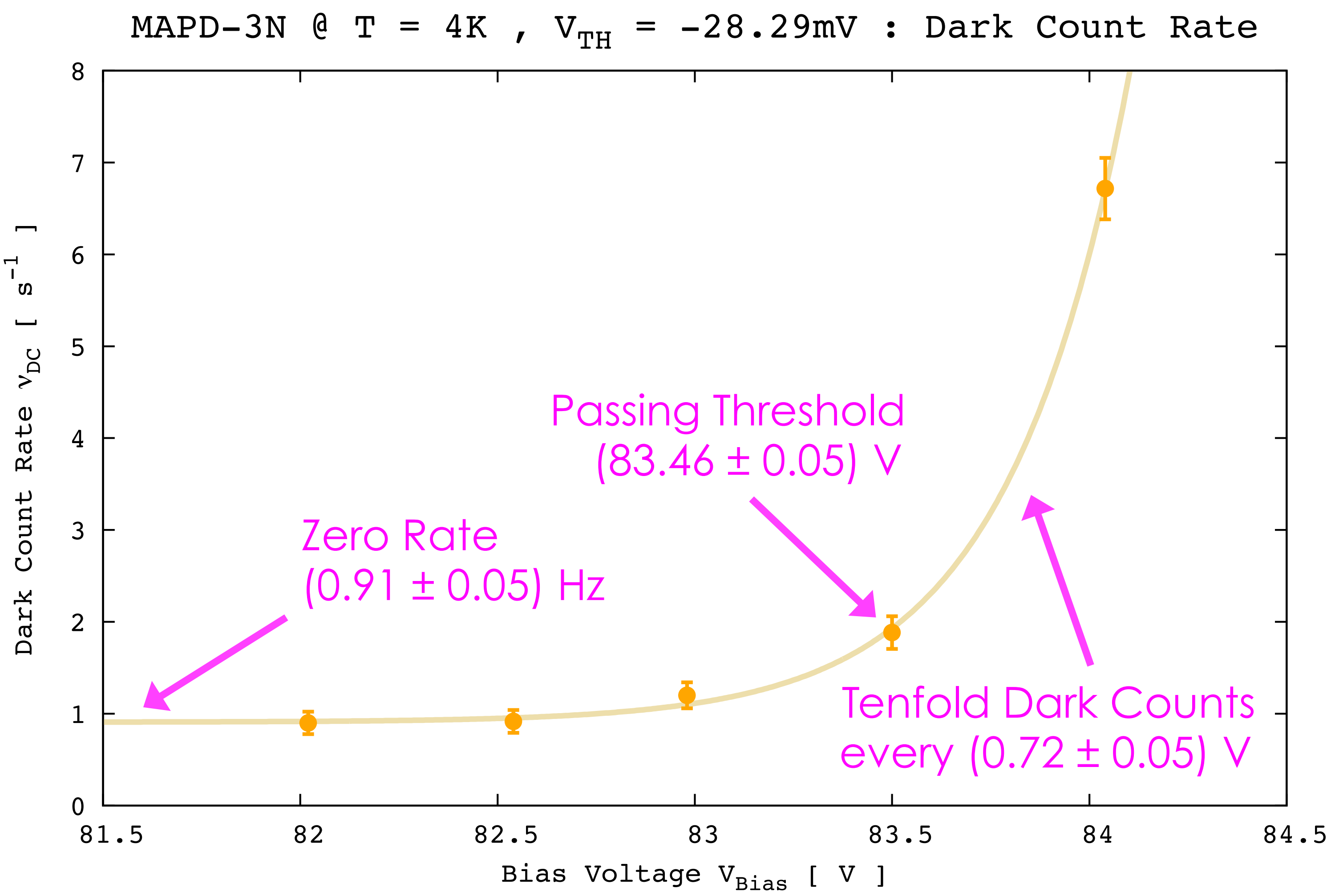
Fall Time
~ 20-30 ns

No After-pulses @ T = 4K



No after-pulses

Few Dark Counts @ V_{TH} = -28.3V, T = 4K



Passing Threshold
(83.46 ± 0.05) V

Zero Rate
(0.91 ± 0.05) Hz

Tenfold Dark Counts
every (0.72 ± 0.05) V

SiPM Spectrum Function of Charge Q

$$P(Q,\lambda)=\sum_{n=1}^{\infty}(1-q)\cdot q^{n-1}\cdot\left[(1-\varphi)+\frac{\varphi\cdot q}{e^{\lambda}-1}\cdot\left(\frac{\Gamma(n+1,\lambda/q)}{\Gamma(n+1)}\cdot e^{\frac{\lambda}{q}}-1\right)\right]\cdot\frac{e^{-\frac{1}{2}\left[\frac{(Q-Q_0-n\cdot G)^2}{\sigma_0^2+n\cdot\sigma_j^2}\right]}}{\sqrt{2\pi\cdot\left(\sigma_0^2+n\cdot\sigma_j^2\right)}}$$

Geometrically Distributed Crosstalk

Dark Count

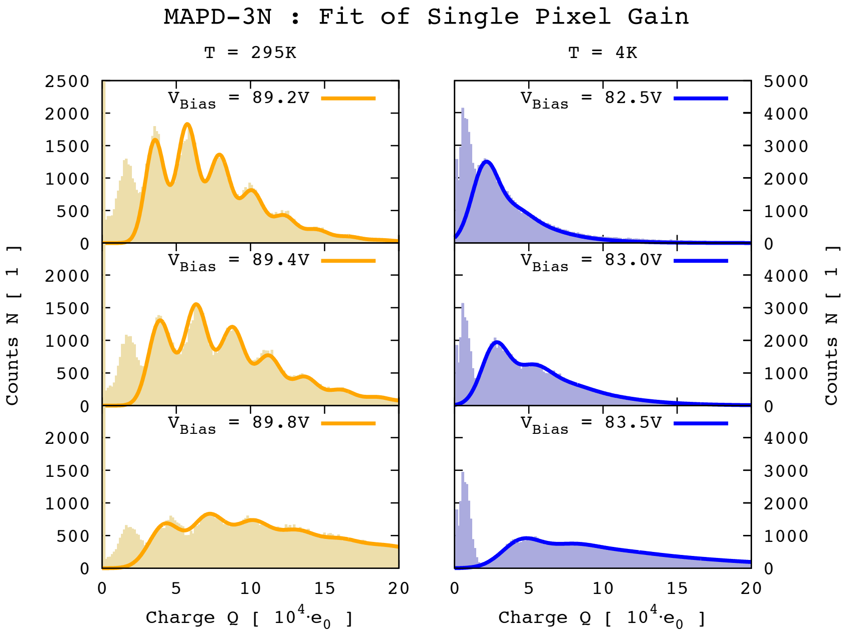
Light Events

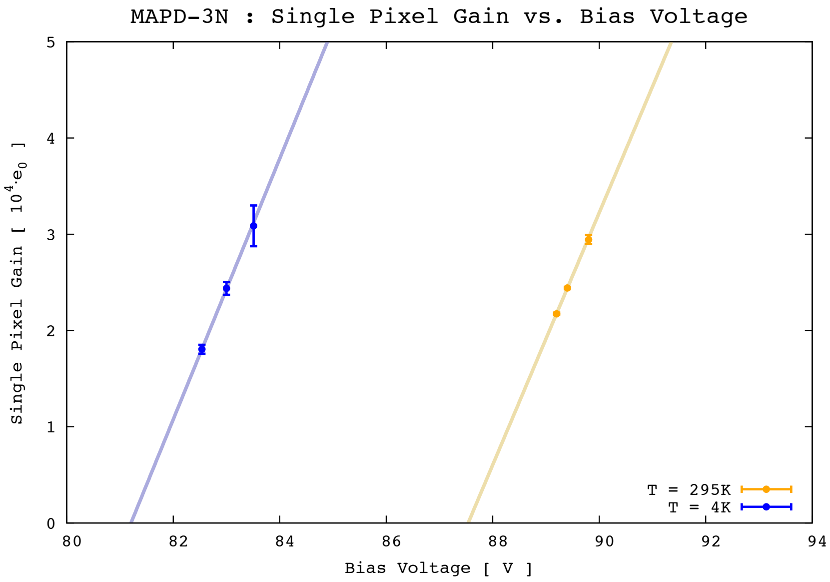
Gaussian Peaks

λ	Average Number of Photons × Quantum Efficiency	n	Number of Fired Pixels
q	Crosstalk Probability	φ	Ratio of Light Events
G	Single Pixel Gain	Q_0	Pedestal
σ_{SV}	Single Pixel Variation	σ_o	Noise Level

[5] Poster ID 85, A Low-noise Fast Pre-amplifier and Readout System for SiPMs

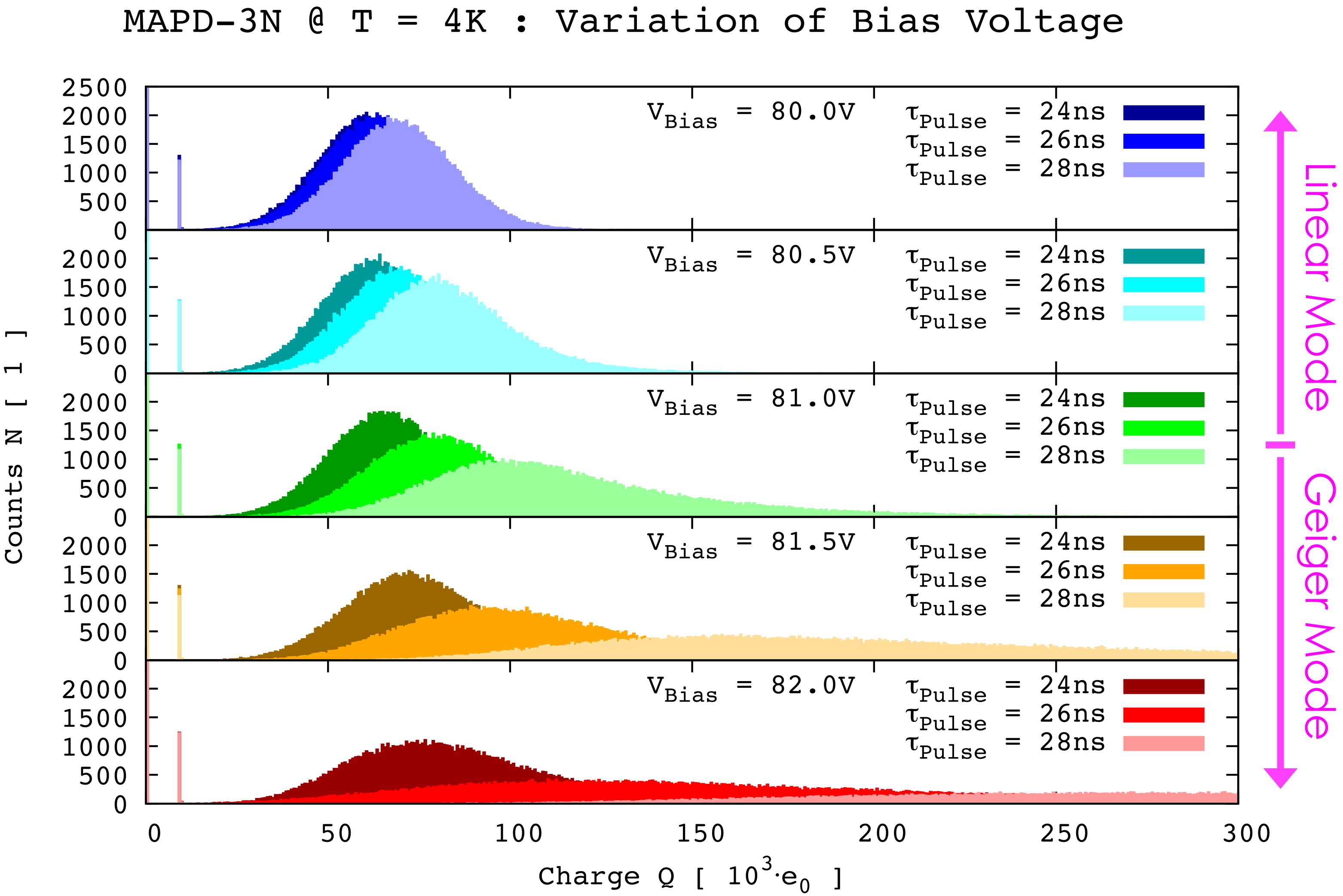
Single Pixel Gain vs. Bias Voltage





Temperature T	**295 K**	**4 K**	➘ (21.9 ± 0.2) mV/K
Break Down Voltage V_{BD}	(87.54 ± 0.04) V	(81.21 ± 0.03) V	
Gain Gradient dG / dV_{Bias}	(1.31 ± 0.03)×10^4 $e_0 V^{-1}$	(1.36 ± 0.03) ×10^4 e_0 V^{-1}	✔

Spectra around V_{BD} @ T = 4K



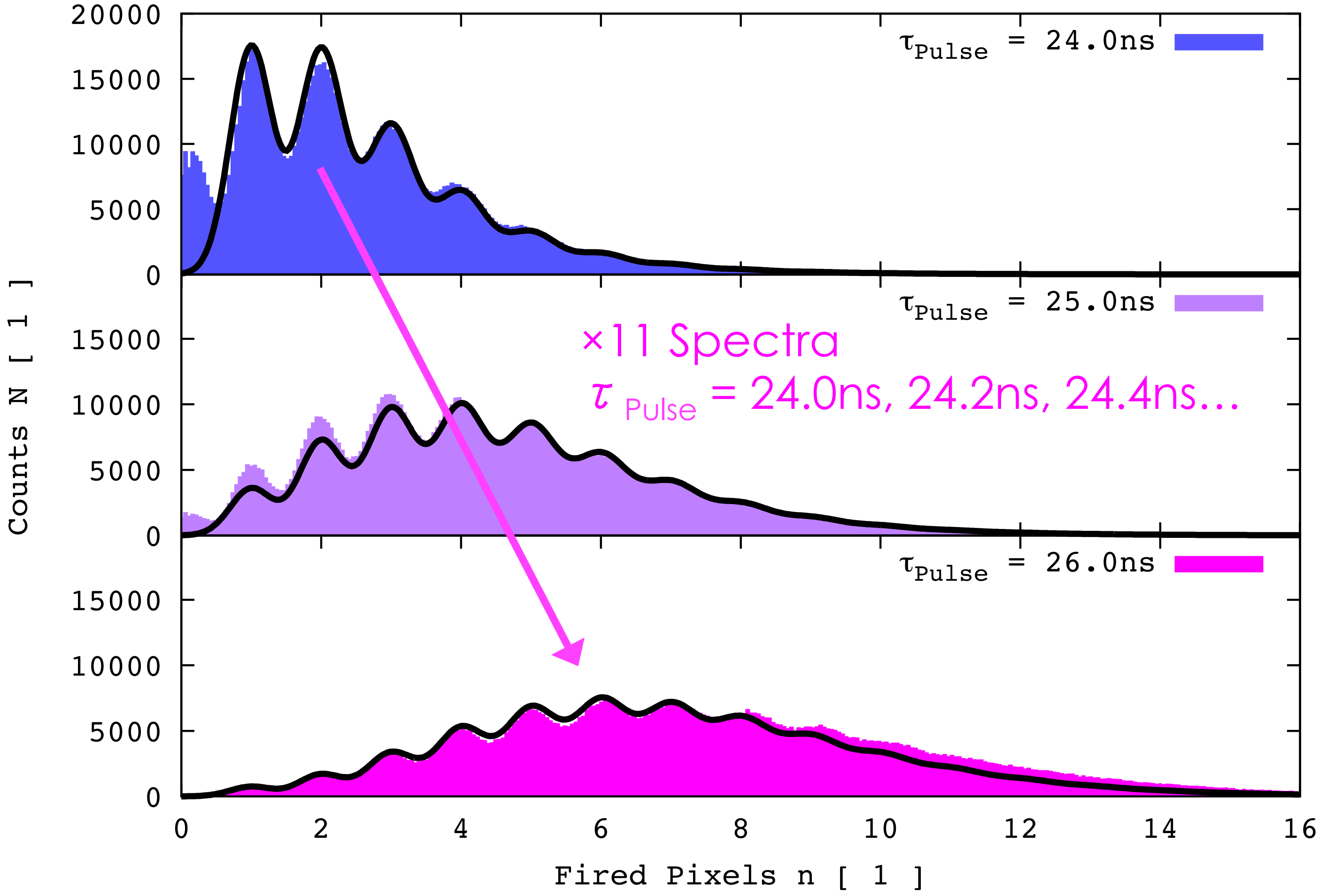
LED Intensity with Square Pulses

Square pulses with width τ ➔ LED intensity is a linear function

$$\lambda(\tau)\Big|_{\tau \geq \tau_0} = \underbrace{\eta \cdot \frac{d\lambda}{d\tau}}_{=:\gamma} \cdot (\tau - \tau_0) = \gamma \cdot (\tau - \tau_0)$$

τ_0	LED Breakdown Gate Width	η	Quantum Efficiency
$d\lambda/d\tau$	LED Light Gain	γ	Light Yield

Intensity Calibration @ T = 295K



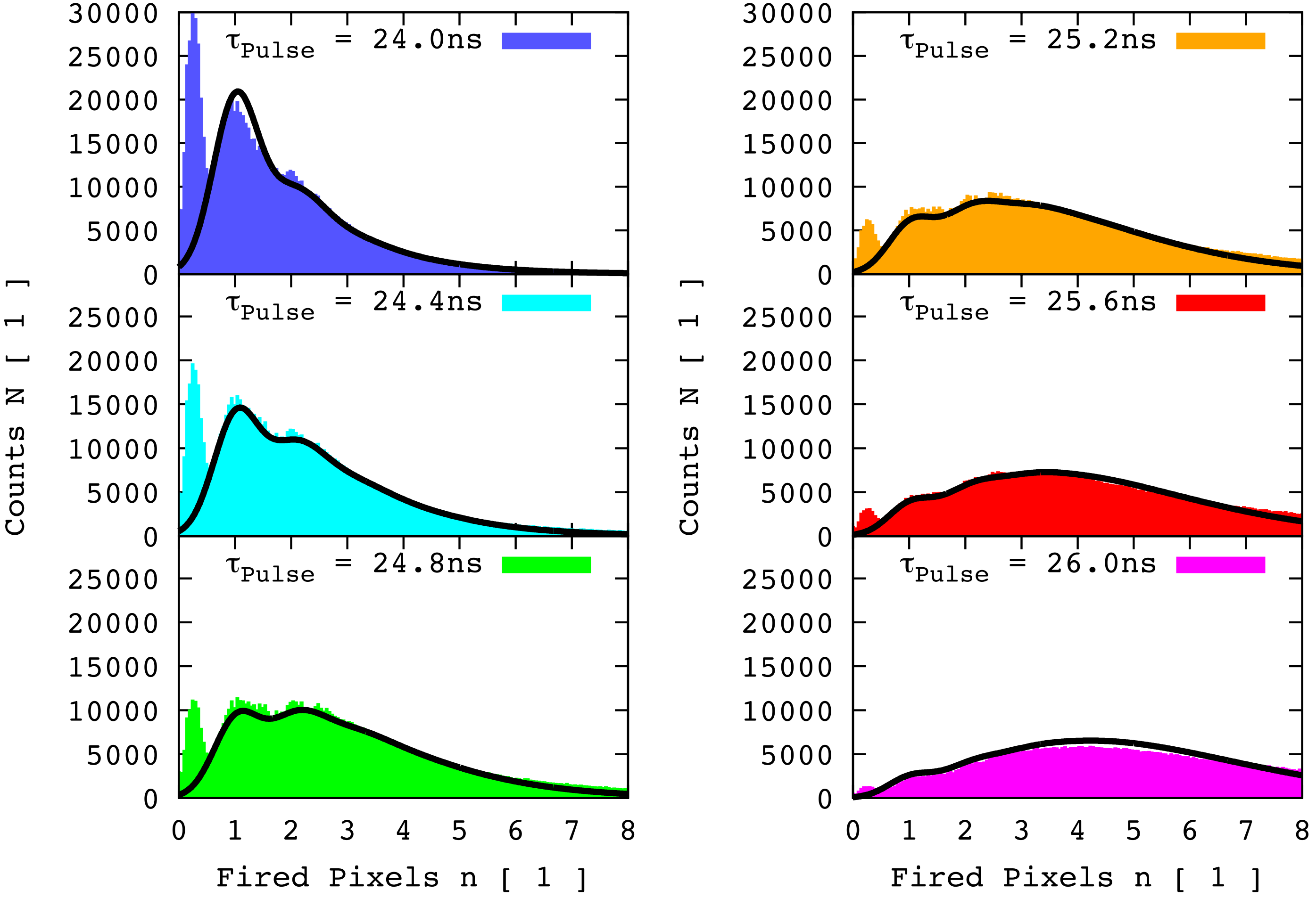
MAPD-3N @ T = 295K , V_{Bias} = 89.98V , $G/e_0 = 2.61 \cdot 10^4$

×11 Spectra

τ_{Pulse} = 24.0ns, 24.2ns, 24.4ns…

Intensity Calibration @ T = 4K

MAPD-3N @ T = 4K , V_{Bias} = 82.87V , $G/e_0 = 2.74\cdot10^4$



Change in Properties @ T = 4 K

Temperature T	**295 K**	**4 K**	✔
Bias Voltage V_{Bias}	89.98 V	82.87 V	
Single Cell Gain G/e_0	$(2.59 \pm 0.01)\times10^4$	$(2.74 \pm 0.10)\ \times10^4$	
Single Cell Variation σ_{SC}/G	(11.1 ± 0.7) % p.e.	(38.6 ± 3.7) % p.e.	
Crosstalk Probability q	(55.9 ± 1.0) %	(42.3 ± 1.8) %	
Light Events Rate φ	(99.2 ± 0.2) %	(97.1 ± 0.5) %	
LED Breakdown Gate Width τ_0	(23.63 ± 0.02) ns	(23.80 ± 0.04) ns	
Light Yield γ	$(2.46 \pm 0.02)\ ns^{-1}$	$(1.94 \pm 0.05)\ ns^{-1}$	

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Single Cell Variation @ T = 4 K

Single Cell Variation caused by fluctuations in quenching

Quenching by a potential wall equals a diode in forward direction[4]
➔ Forward voltage equals height of potential wall

Temperature T	295 K	4 K
Forward Voltage V_{FW} @ 820 μ A	0.579 V	1.964 V

$$\frac{V_{FW}(T=4K)}{V_{FW}(T=295K)} = 3.4 \quad \Longleftrightarrow \quad \frac{\sigma_{SV}(T=4K)}{\sigma_{SV}(T=295K)} = 3.5 \pm 0.4$$

[4] Z. Sadygov et al. Performance of new
Micro-pixel Avalanche Photodiodes from Zecotek.
Nucl. Instrum. and Meth. A, 610:381–383, 2009

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Crosstalk Probability q	(55.9 ± 1.0) %	(42.3 ± 1.8) %	➘ - 24 %
Light Events Rate φ	(99.2 ± 0.2) %	(97.1 ± 0.5) %	
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Light Yield γ	(2.46 ± 0.02) ns^{-1}	(1.94 ± 0.05) ns^{-1}	↘ - 21 %

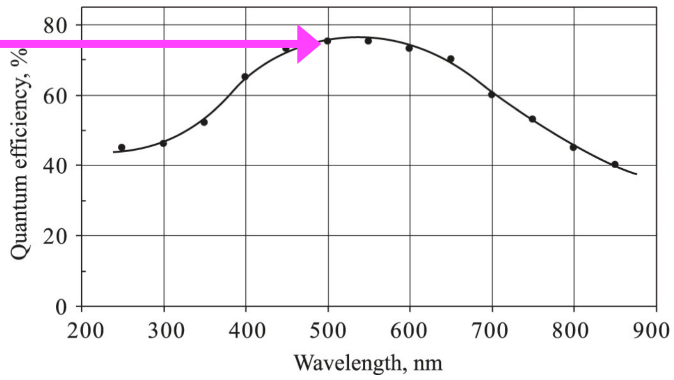
Quantum Efficiency η @ T = 4 K

$$\gamma(T) = \eta(T)\cdot\frac{d\lambda}{d\tau} \quad \Longleftrightarrow \quad \frac{\eta(T=4K)}{\eta(T=295K)} \cong \frac{\gamma(T=4K)}{\gamma(T=295K)} = (79\pm 2)\%$$

Temperature T	**295 K**	**4 K**
Quantum Efficiency η @ 475nm	32 %[3]	(25.2 ± 0.8) %

For the MAPD-3B quantum efficiency of 15% is given (400nm-600nm)[3]

But without the epoxy cover
➔ η increases over 70%[4]



[3] *Zecotek MAPD White Paper*
Zecotek Photonics, Richmond, Canada, 2011

[4] *Z. Sadygov et al. Performance of new*
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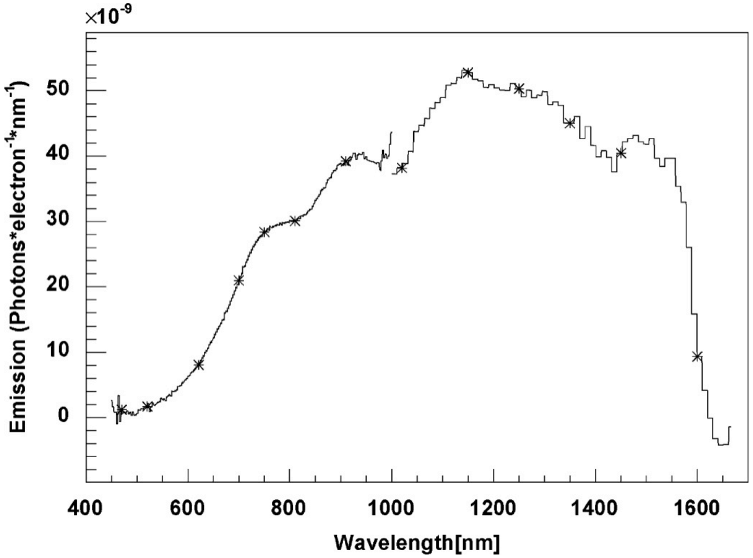
Crosstalk Probability q @ T = 4 K



Hot carrier emission spectrum in Si avalanches[6]

Crosstalk is an optical emission and absorption process, so it is correlated to quantum efficiency

$$\frac{q(T=4K)}{q(T=295K)} = (76 \pm 3)\%$$

↕

$$\frac{\eta(T=4K)}{\eta(T=295K)} = (79 \pm 2)\%$$

Lower crosstalk probability consistent with lower quantum efficiency

[3] Zecotek MAPD White Paper
Zecotek Photonics, Richmond, Canada, 2011

[6] R. Mirzoyan et al. Light Emission in Si avalanches
Nucl. Instrum. and Meth. A, 610 : 98 - 100, 2009

Conclusion

- Operating SiPMs at cryogenic temperatures is possible with one particular type from Zecotek
- At T = 4K we observed:
  - ✓ No after-pulses
  - ✓ Extremely low dark count rate
  - ✓ Only small change in quantum efficiency

Thank you for your attention!