MuPix and ATLASpix Architectures and Results

Vertex 2019 Workshop

Lopud Island, 14.-18. October, 2019

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on behalf of the Mu3e and ATLAS HV-CMOS collaborations

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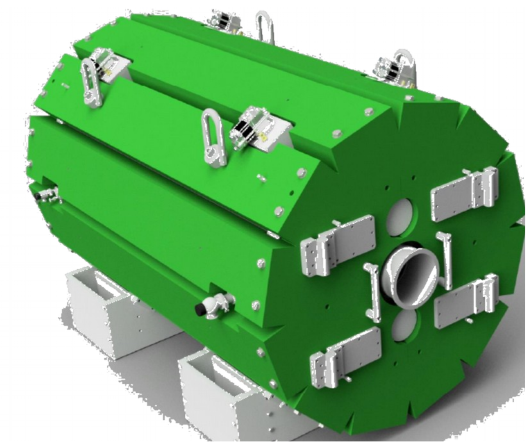
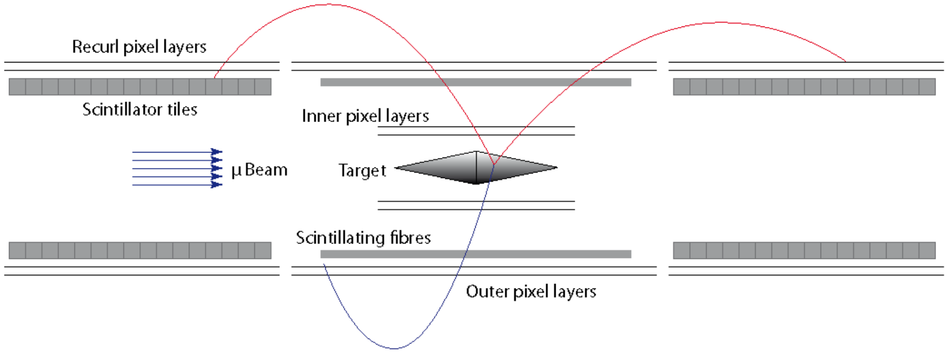
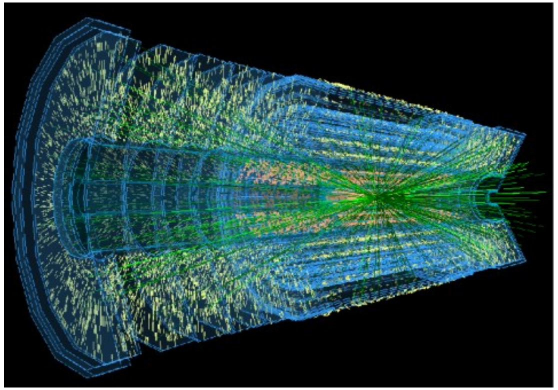
MuPix for Mu3e & ATLASpix for ATLAS

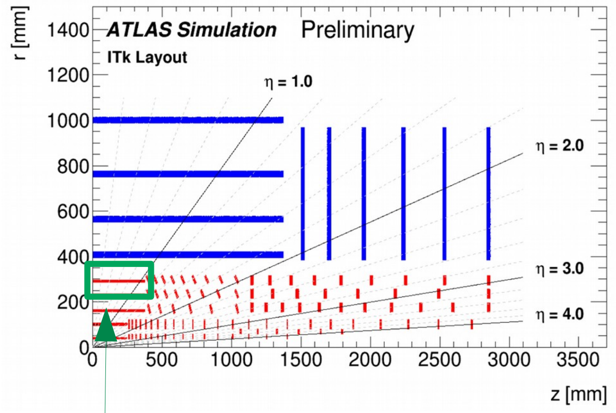




- Search for $B(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-15} - 10^{-16}$
- 10^8-10^9 muon decays (tracks) per second

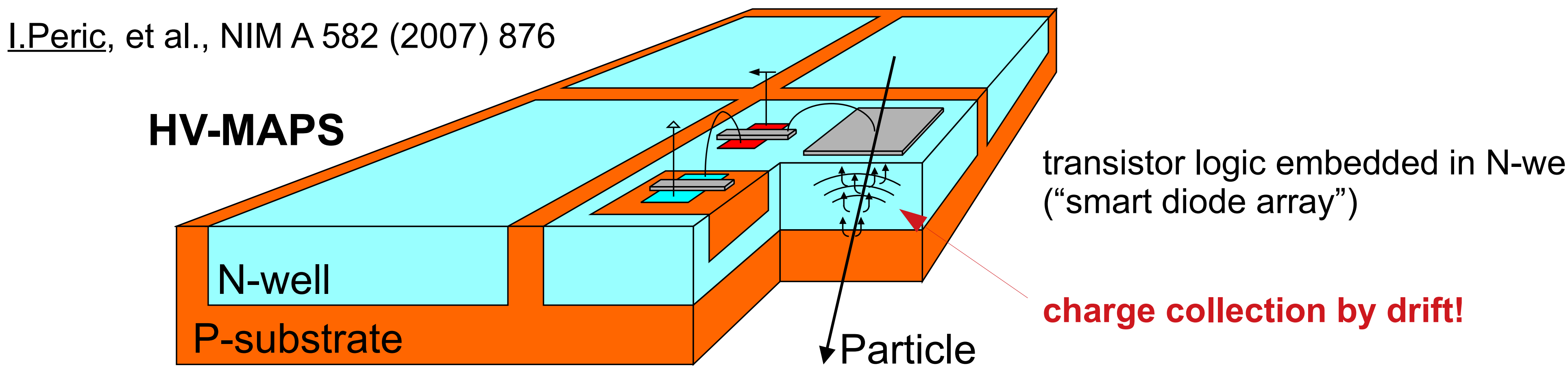
→ see Mu3e talk by Frank Meier (Thursday)





- Multi-purpose Experiment @ LHC
- Alternative for ITK Pixel Tracker (HL-LHC)

High Voltage - Monolithic Active Pixel Sensor

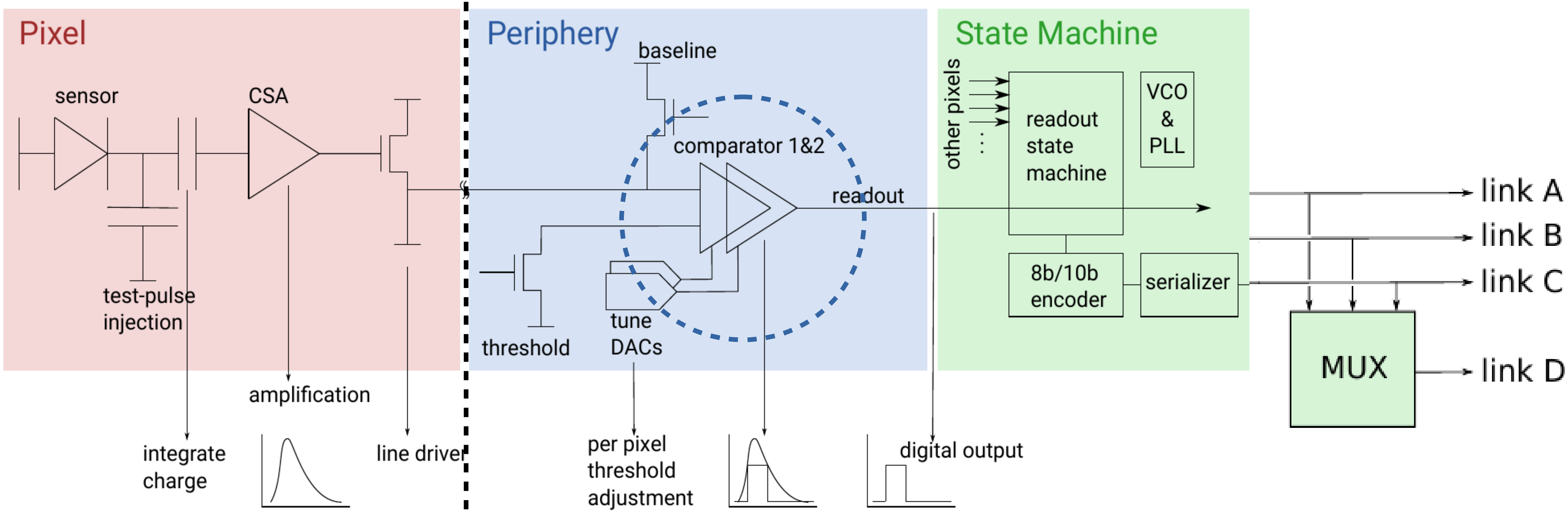


active sensor → hit finding & digitisation & zero suppression & readout

- low noise O(50e) → low threshold
- small depletion region of ≤ 30 μm → thin sensor ~50 μm
- standard HV-CMOS (60 - 120 V) process → low production costs
- continuous and fast readout (serial link) → high rate applications

Example: Mupix8 Architecture

MuPix8

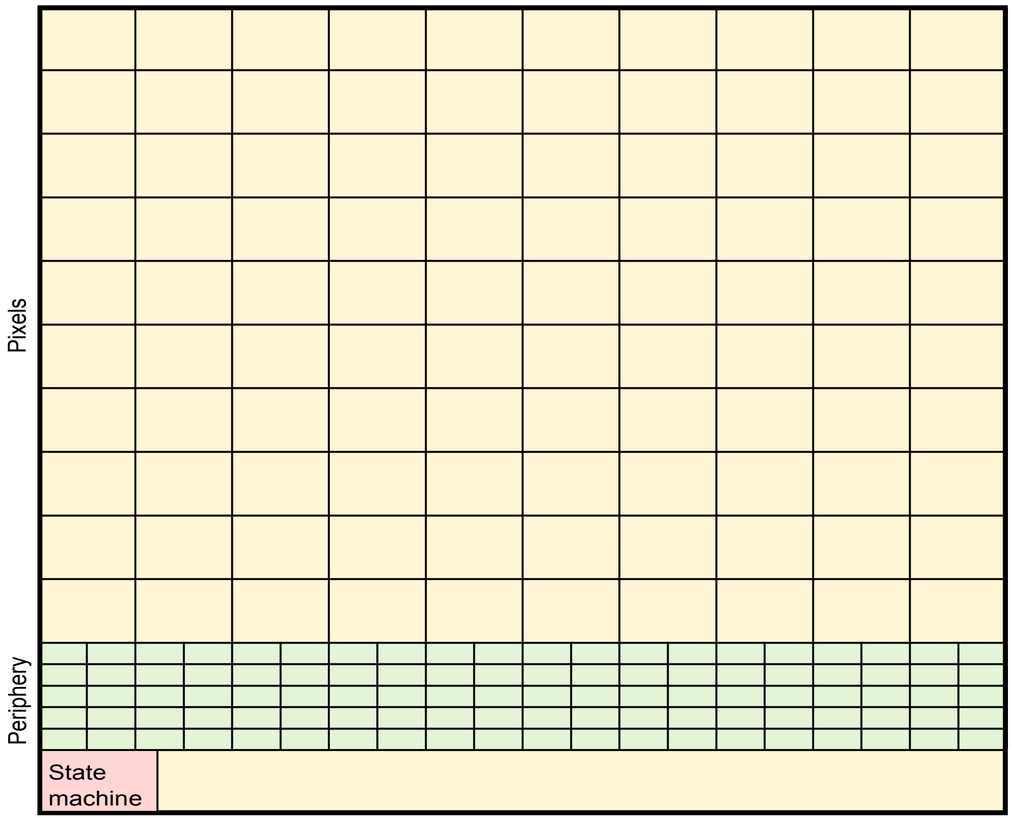


MuPix8

periphery & SM

MuPix Chip Design

column drain RO



"real" cells

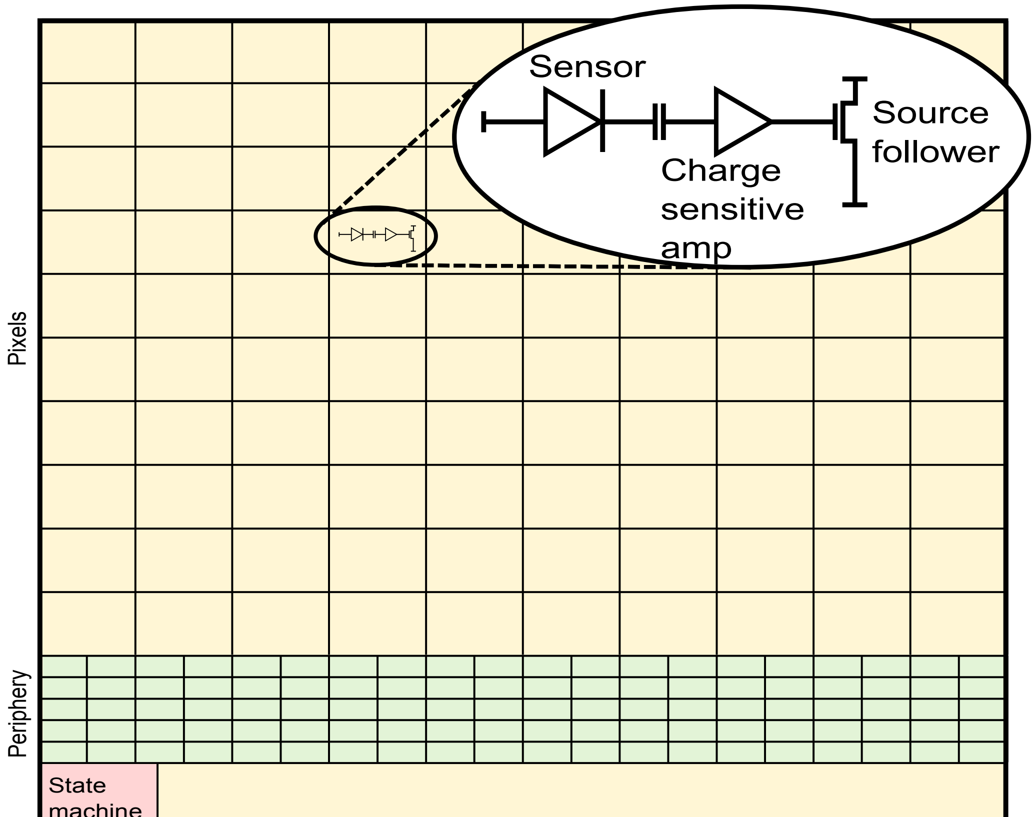
active pixel matrix

"mirror" cells

state machine
VCO, PLL, ...

periphery
(5-10% total area):

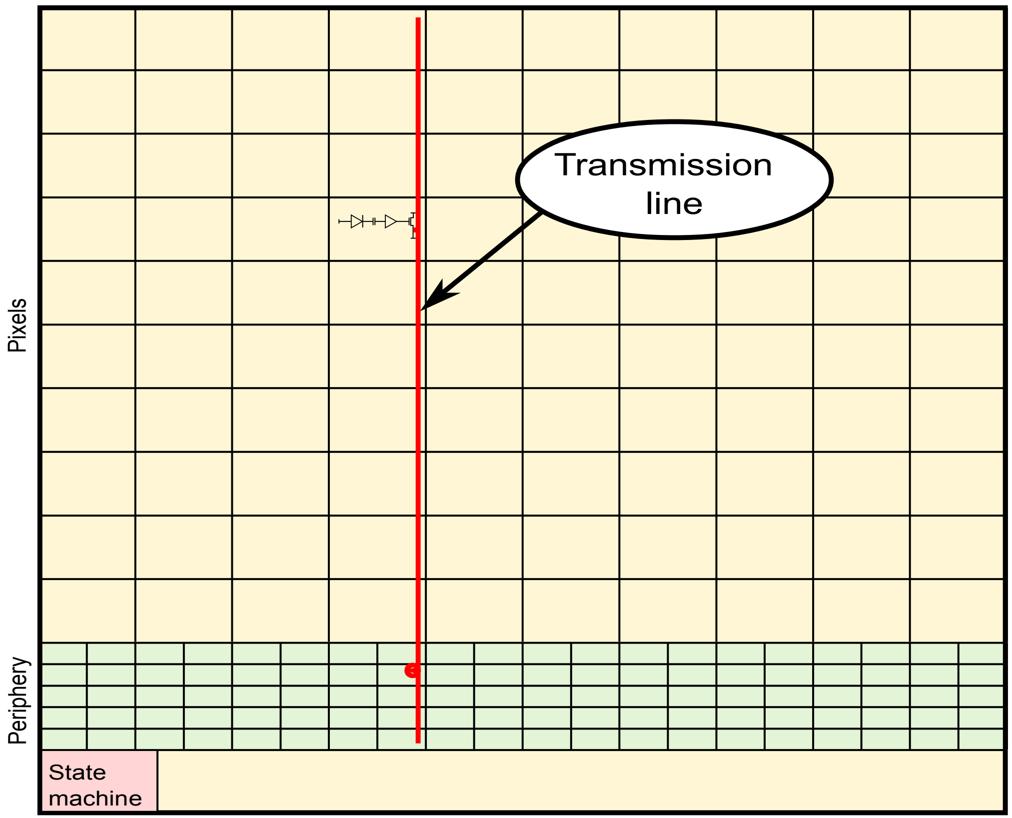
MuPix Chip Design



analog cell:

- reverse biased -85V
- charge sensitive amplifier
- source follower

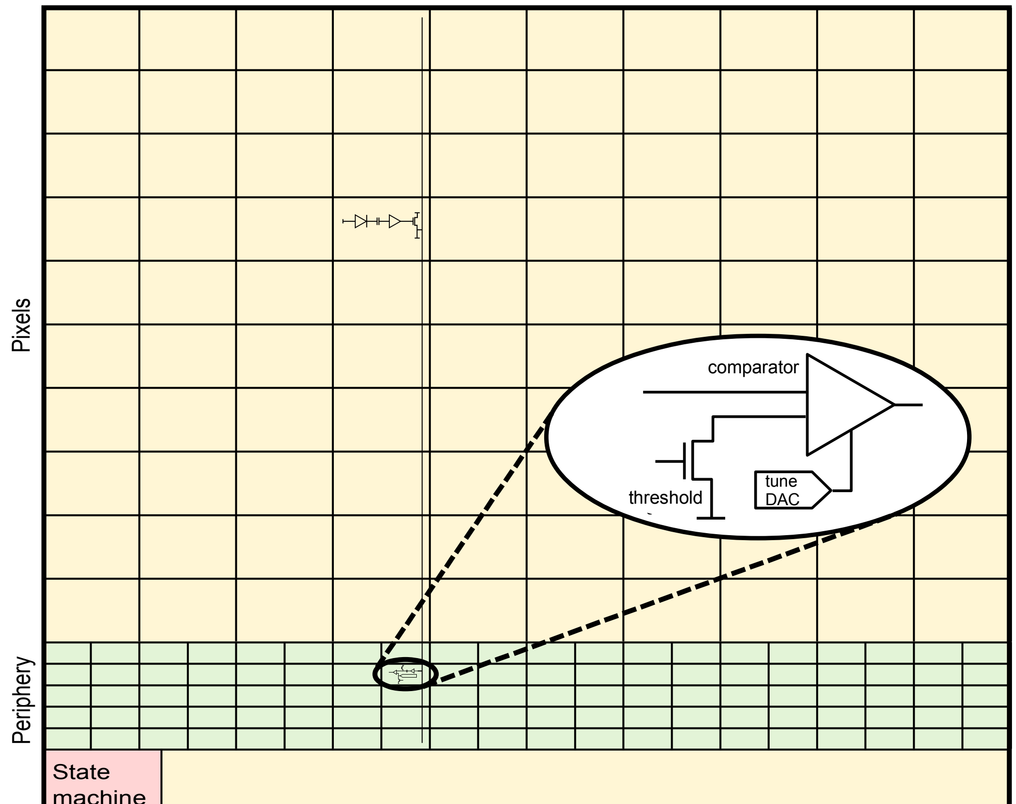
MuPix Chip Design



transmission line:

- send signal to corresponding mirror cell

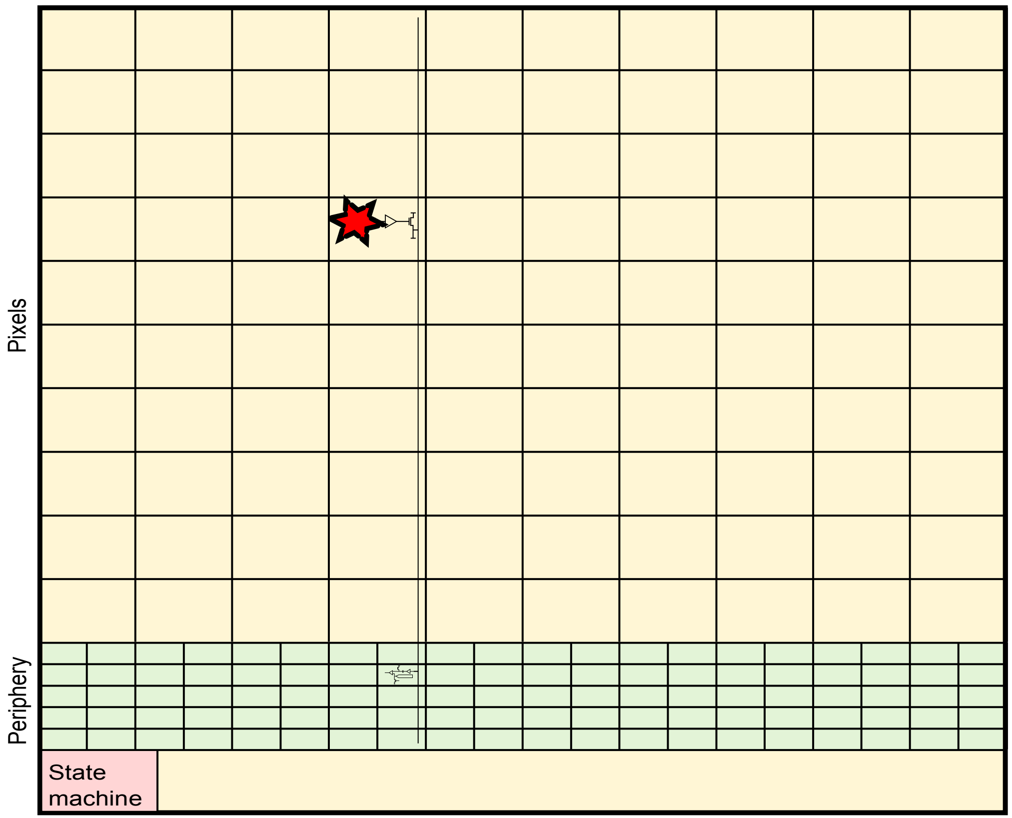
MuPix Chip Design



mirror cell:

- comparator for discrimination
- threshold and baseline by tuning DACs

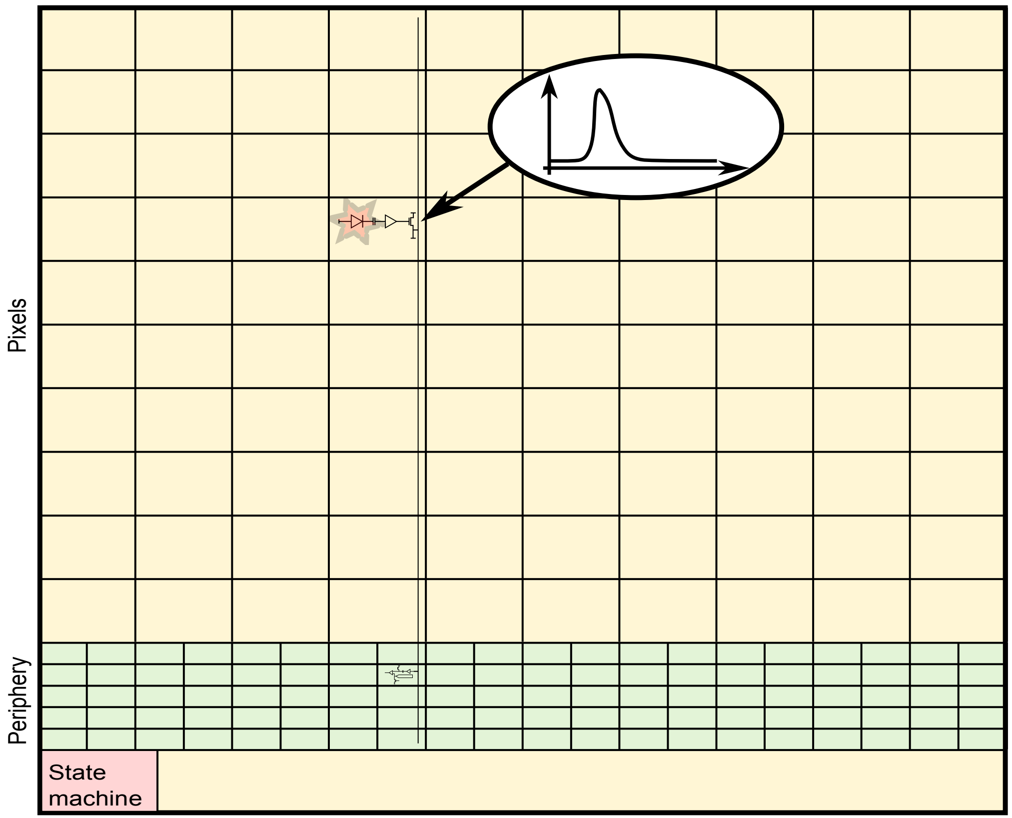
MuPix Chip Design



hit sequence:

- signal generation

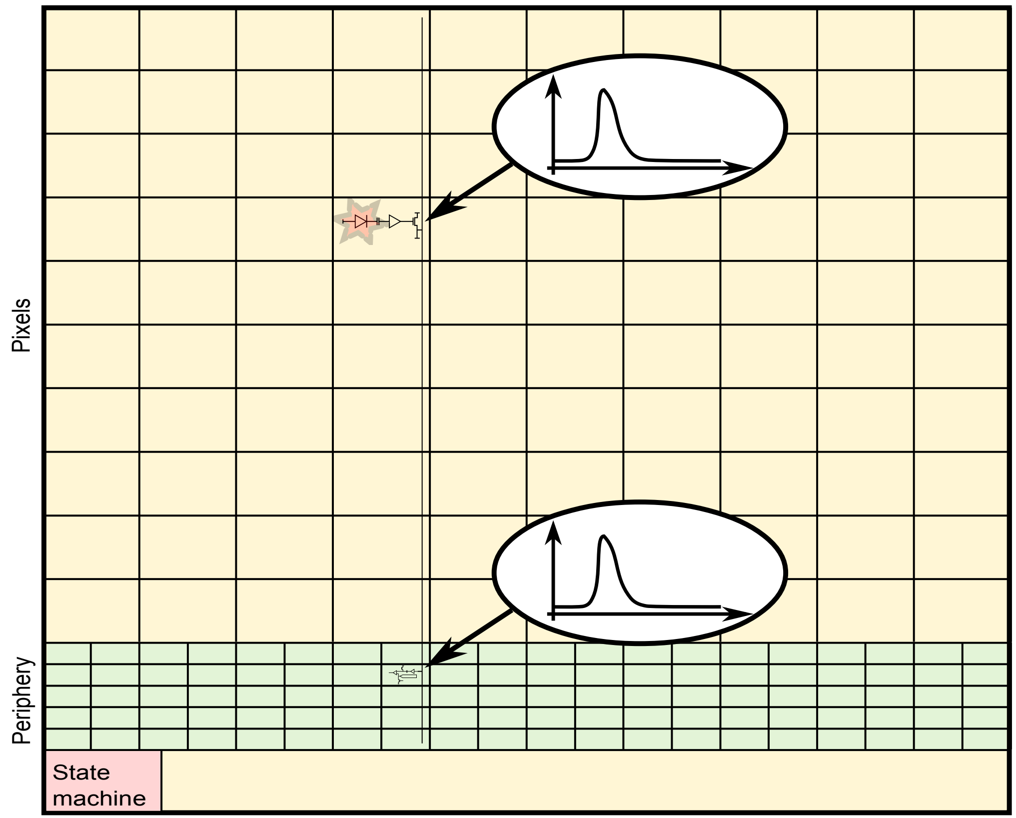
MuPix Chip Design



hit sequence:

- signal generation
- amplification

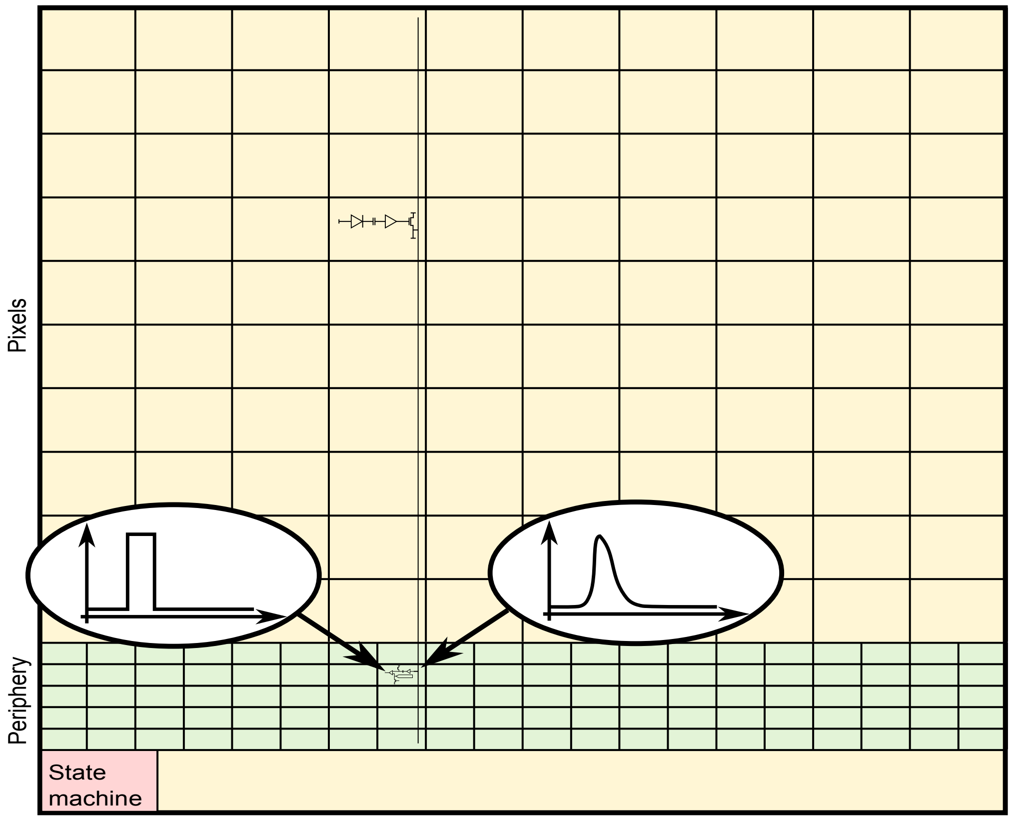
MuPix Chip Design



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel

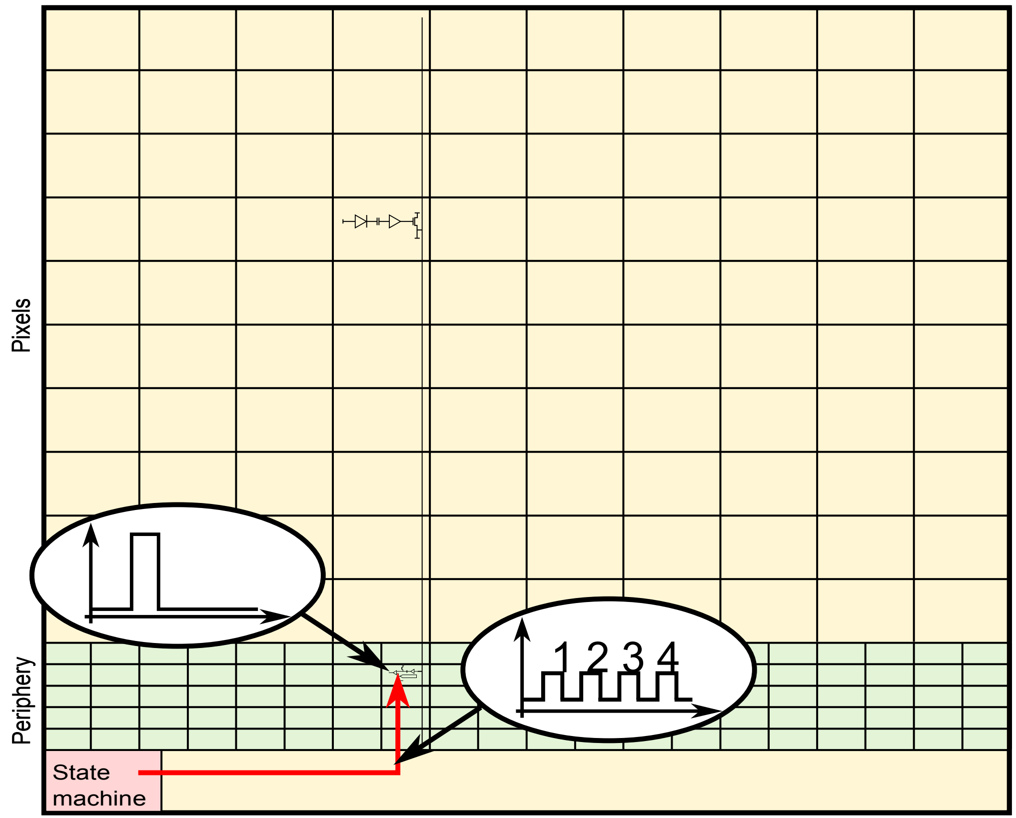
MuPix Chip Design



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated

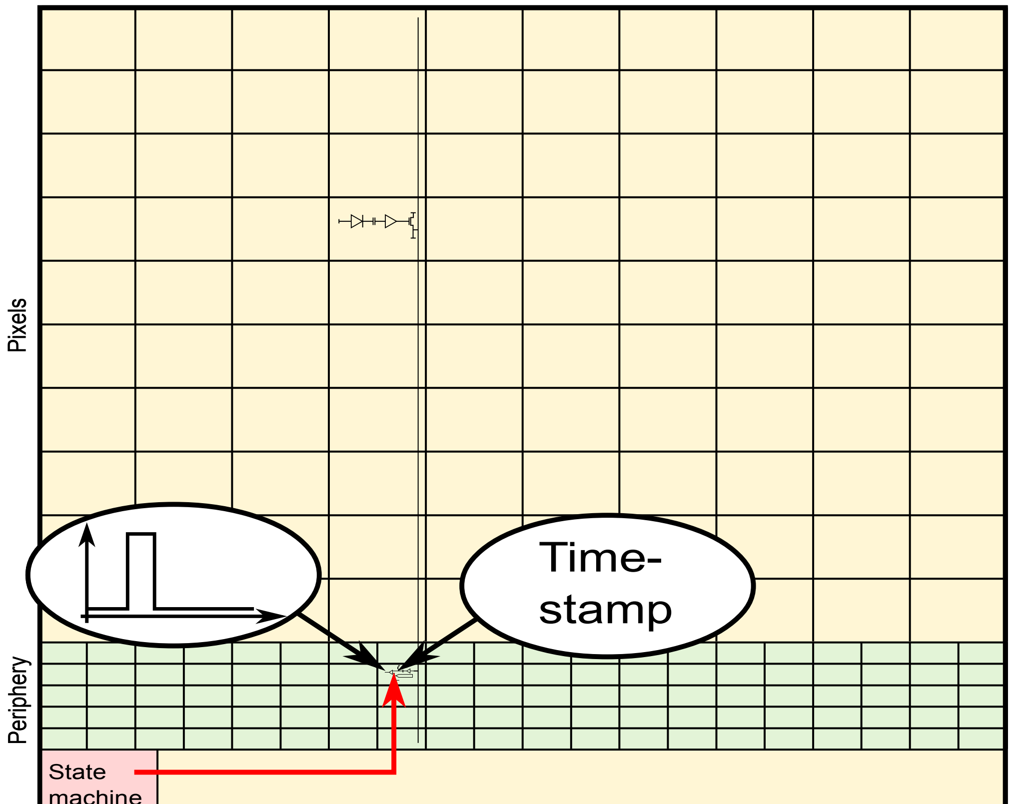
MuPix Chip Design



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk

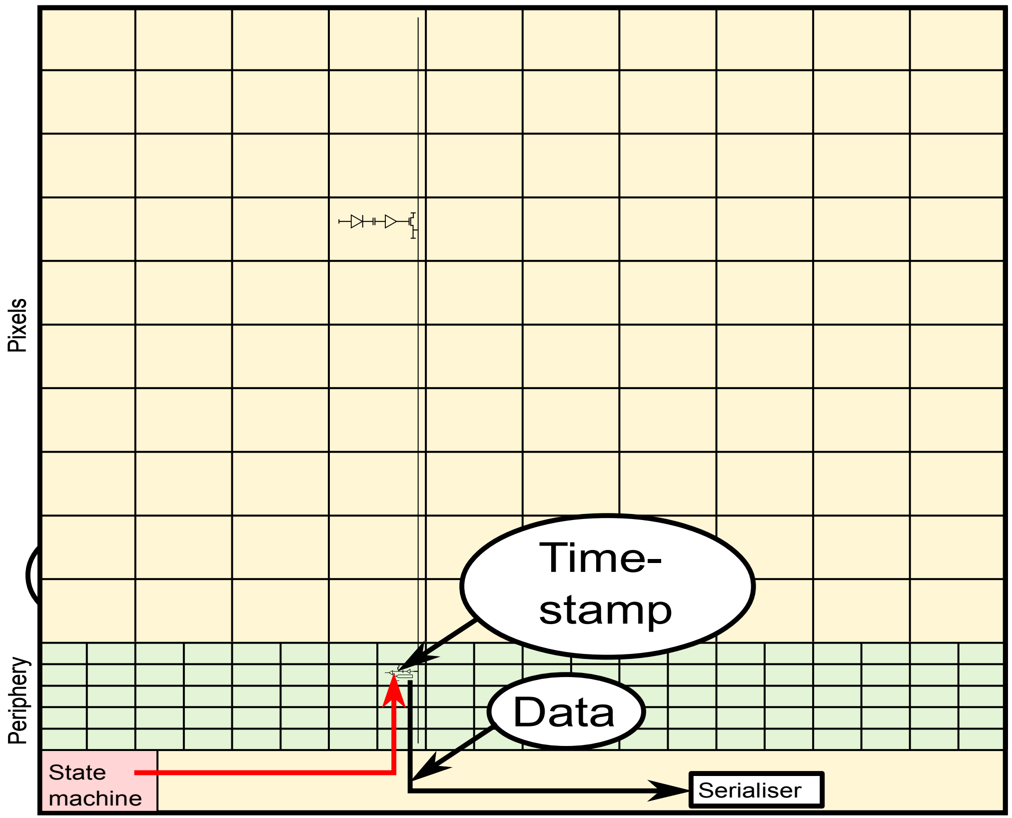
MuPix Chip Design



hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation

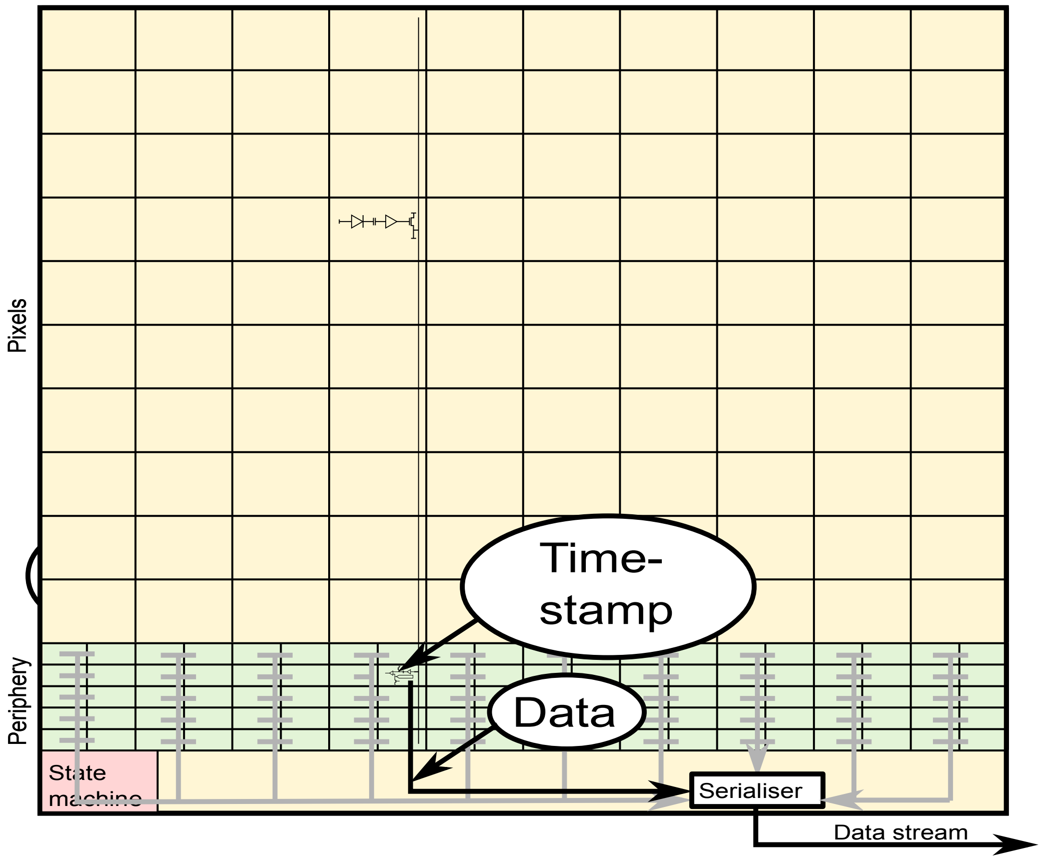
MuPix Chip Design



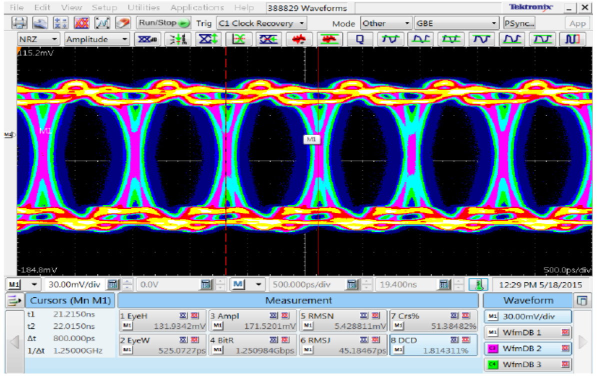
hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation
- hit address and timestamp send to serializer

MuPix Chip Design



Finally, **all detected hits** are sent out via a serial link **1.25 -1.6 Gbit/s**

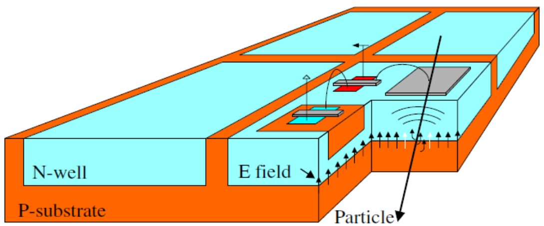


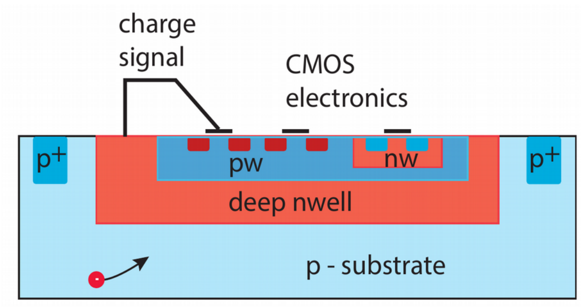
Eye diagram measured with Mupix prototype

Maximum readout rate is 33 Mhits/s per link

HV-MAPS Prototypes - History

I. Peric et al (2007)

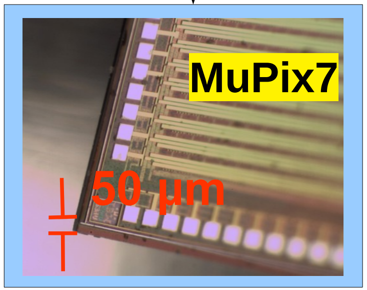




Mupix7 was the first small scale prototype integrating all relevant features of a **fully monolithic chip** (VCO, PLL, state machine, ...)

Mu3e-Experiment

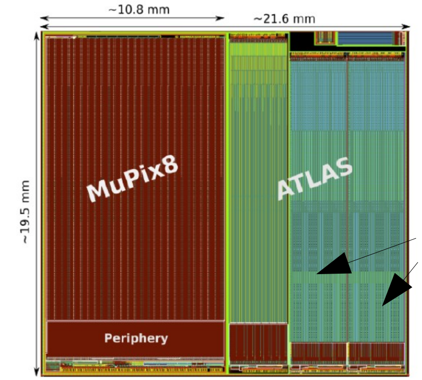
MuPix1 → MuPix2 → ...... → MuPix6 →



AMS H18 (IBM)

Mu3e & ATLAS (HL-LHC)

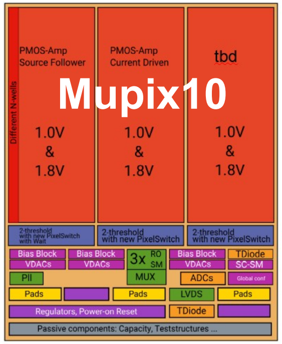
AMS AH18

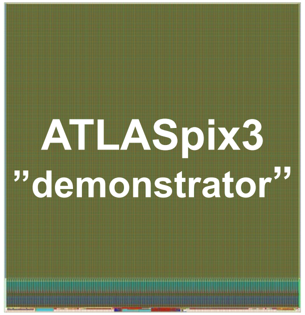


ATLASpix1

Mupix9 | ATLASpix2

TSI H18



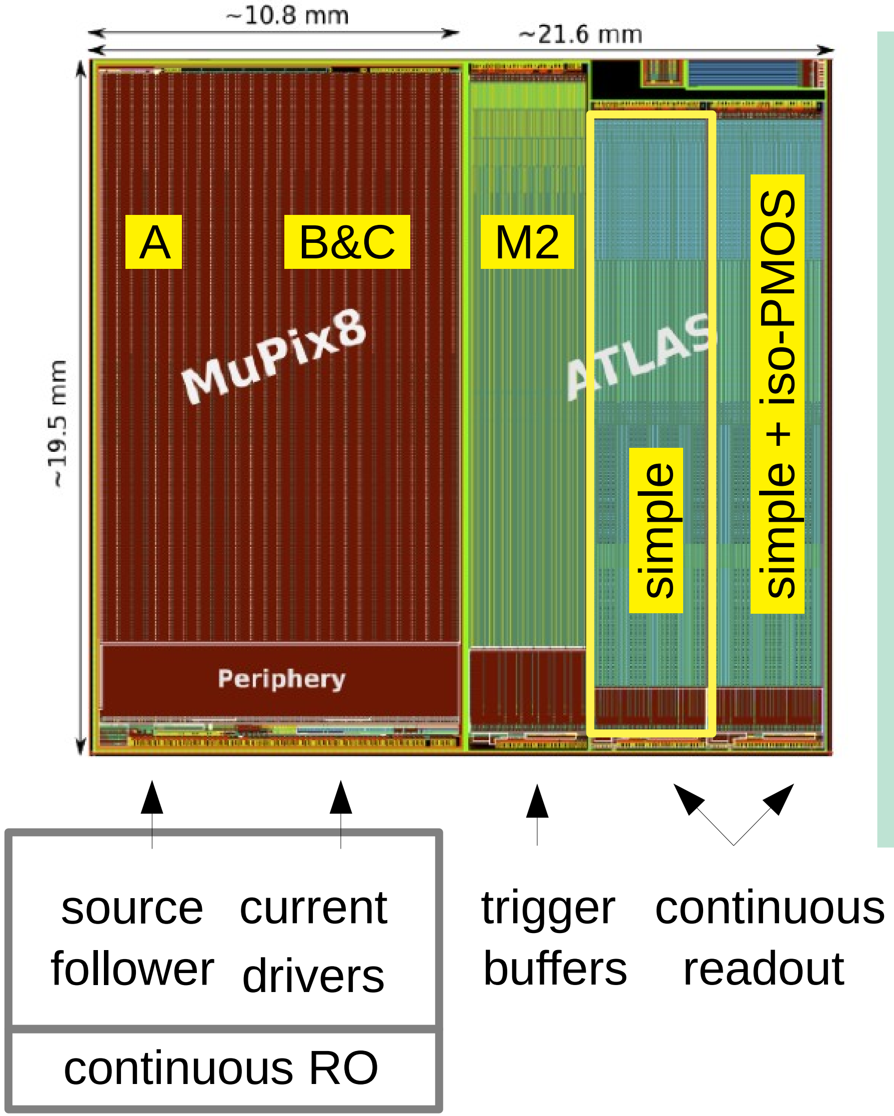


NEW!

MuPix8 & ATLASpix1

Mupix8

- pixel: 80 x 81 μm^2
- 200 rows x 48 cols
- amplifier in pixel cell
- **discriminators in periphery**
- 6 bit ToT
- state machine
- serial link up to 1.6 Gbit/s

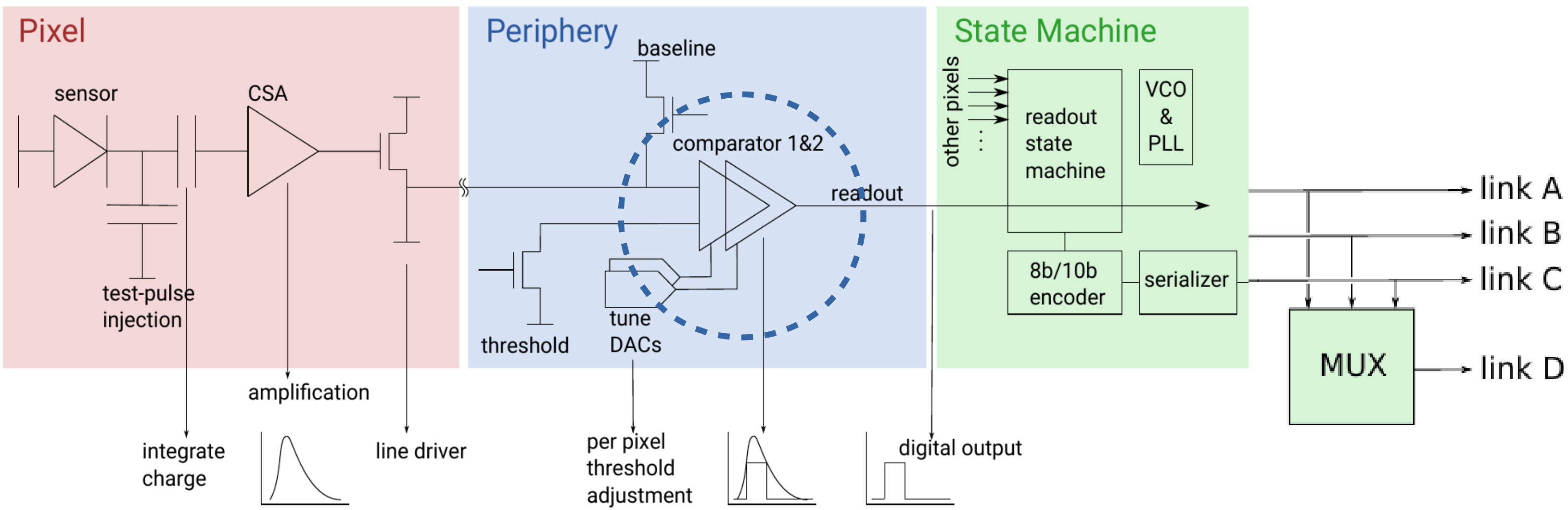


ATLASpix

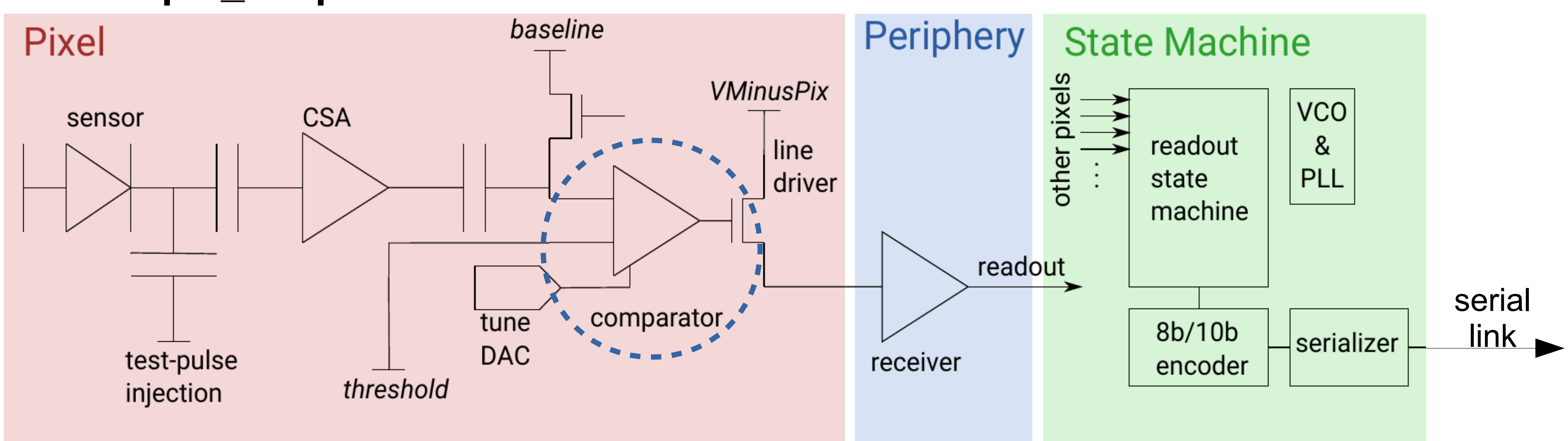
- pixel: 40 x 130 μm^2
- 400 rows x 25 cols
- amplifier in pixel cell
- **discriminators in active pixel cell**
- 6 bit ToT
- state machine
- serial link up to 1.6 Gbit/s

Mupix8 versus ATLASpix_simple

MuPix8



ATLASpix_simple



Results in the following ...

Lab characterisations

- charge injection
- radioactive sources
- LED, Laser
- X-Ray fluorescence
- ...

Large number of testbeams (exploiting several telescopes):

- CERN: pions 180 GeV
- DESY: electrons 3-6 GeV
- Fermilab: pions 180 GeV
- MAMI: electrons ~870 MeV → very focused beam & high rate!
- PSI: pions ~250 MeV/c, protons ~500 MeV/c → high rate!

Mu3e MuPix & ATLAS HV-CMOS Collaborations

Argonne NATIONAL LABORATORY

BROOKHAVEN NATIONAL LABORATORY

CLIC

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

IFAE Institut de Física d'Altes Energies

INFN

KIT Karlsruher Institut für Technologie

u^b UNIVERSITÄT BERN

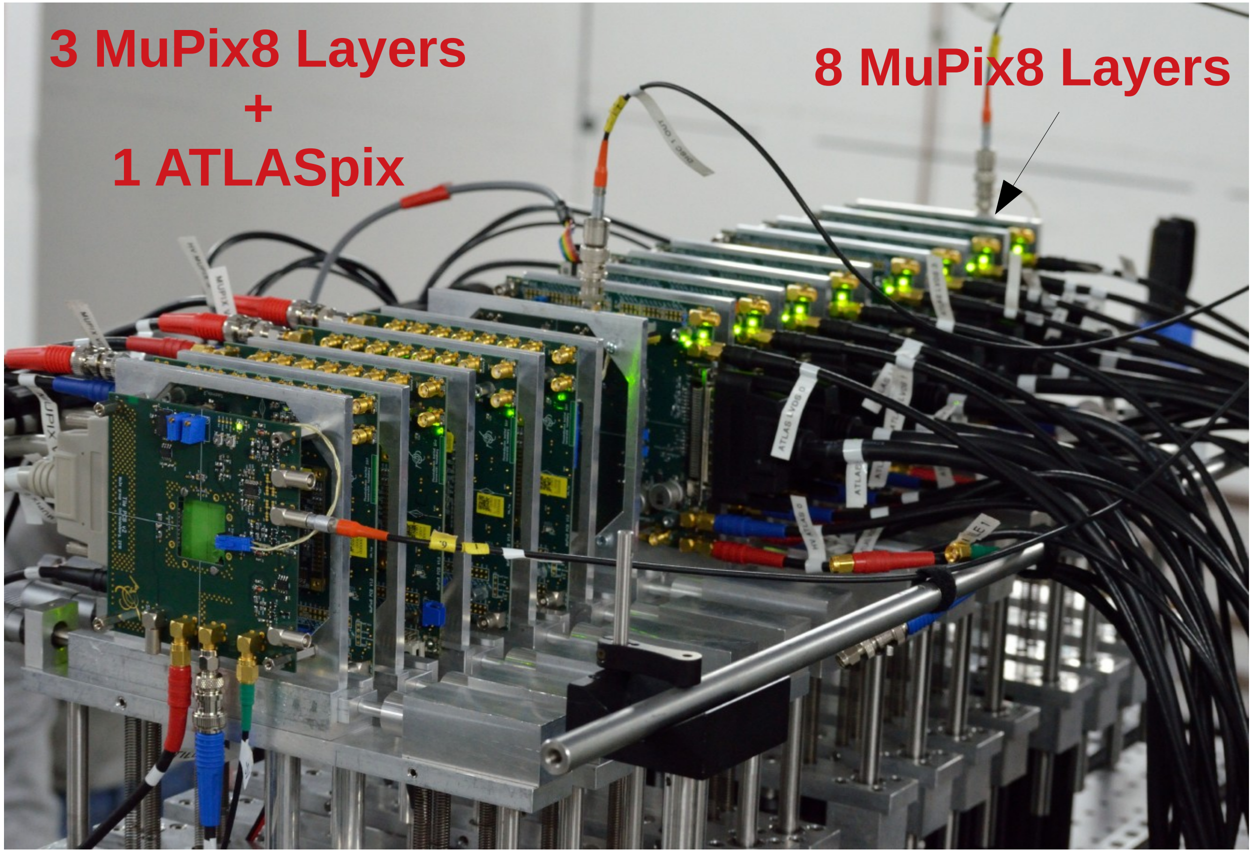
UNIVERSITÉ DE GENÈVE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

UNIVERSITY OF LIVERPOOL

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

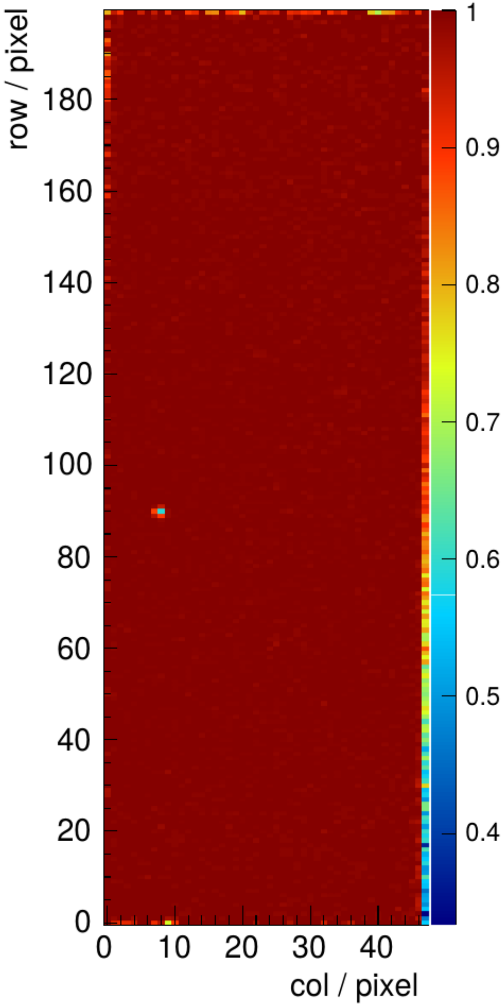
MuPix/ATLASpix (HV-MAPS) Telescope



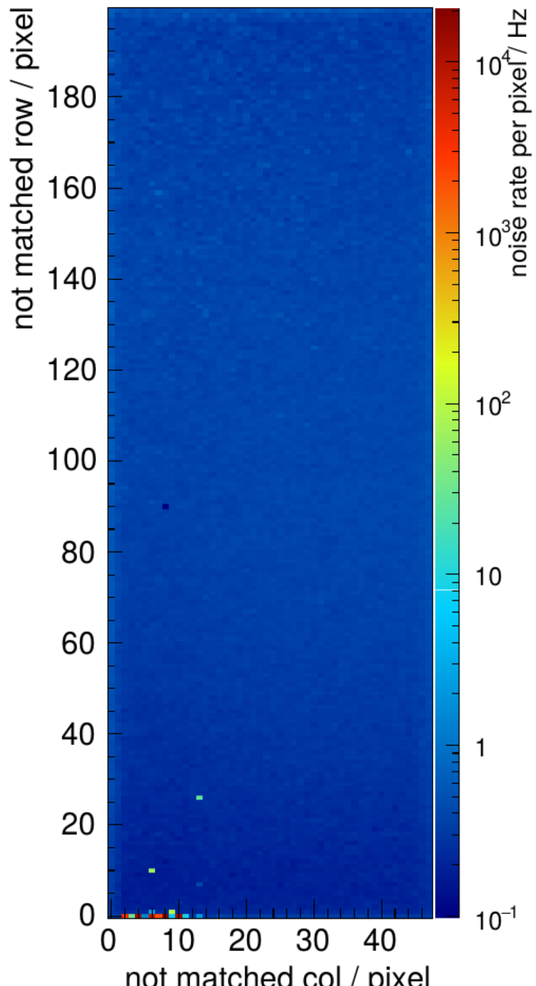
- HV-MAPS fully integrated as telescope layers (since 2013)
- O(10) telescopes built (Mupix6,7,8 & ATLASpix)
- long experience in reliably operating HV-MAPS with high particle rates (up to 2.5 MHz)

Mupix8 Performance Plots

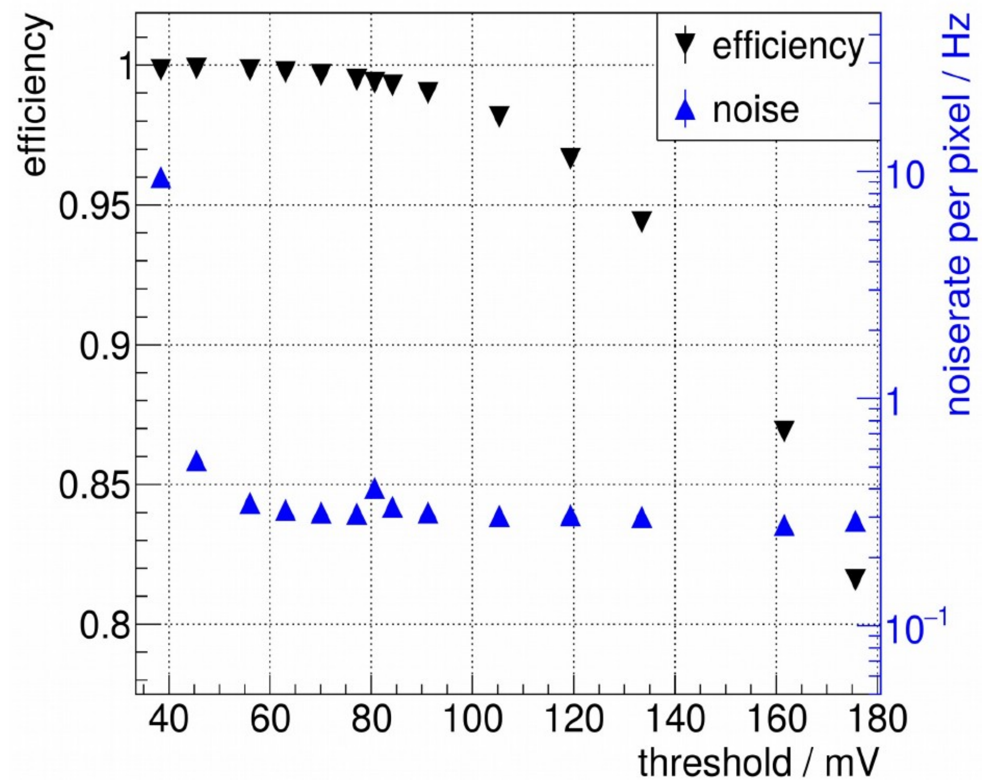
efficiency
~99.9%



noise
~1Hz/pixel

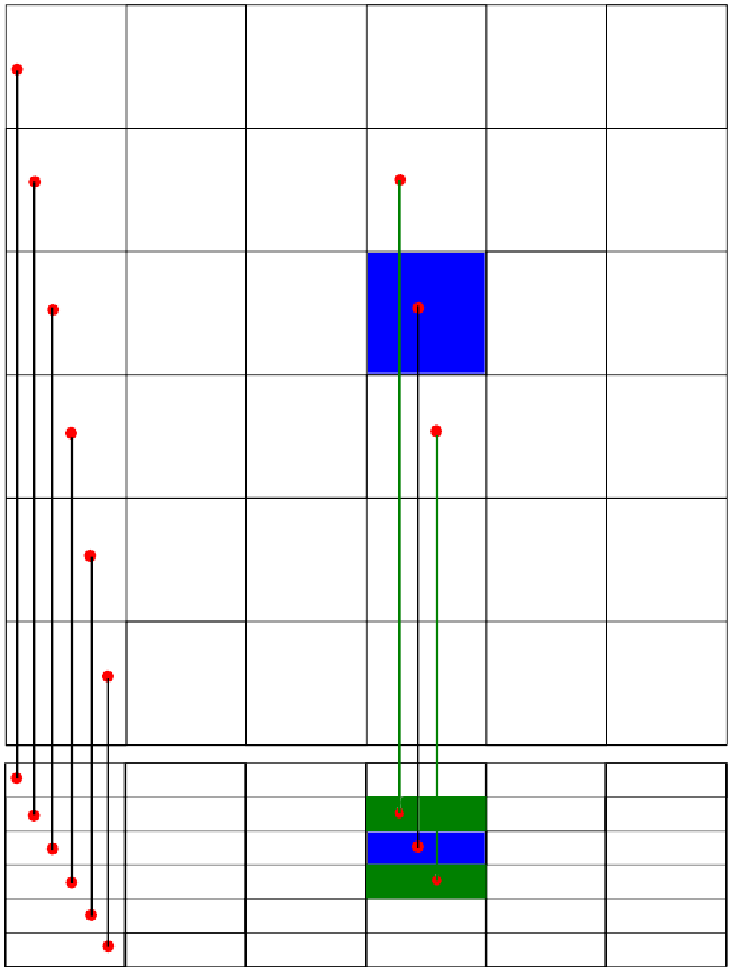


80 Ω cm



100mV ~ 1300 e^-

Mupix/ATLASpix Readout Architecture



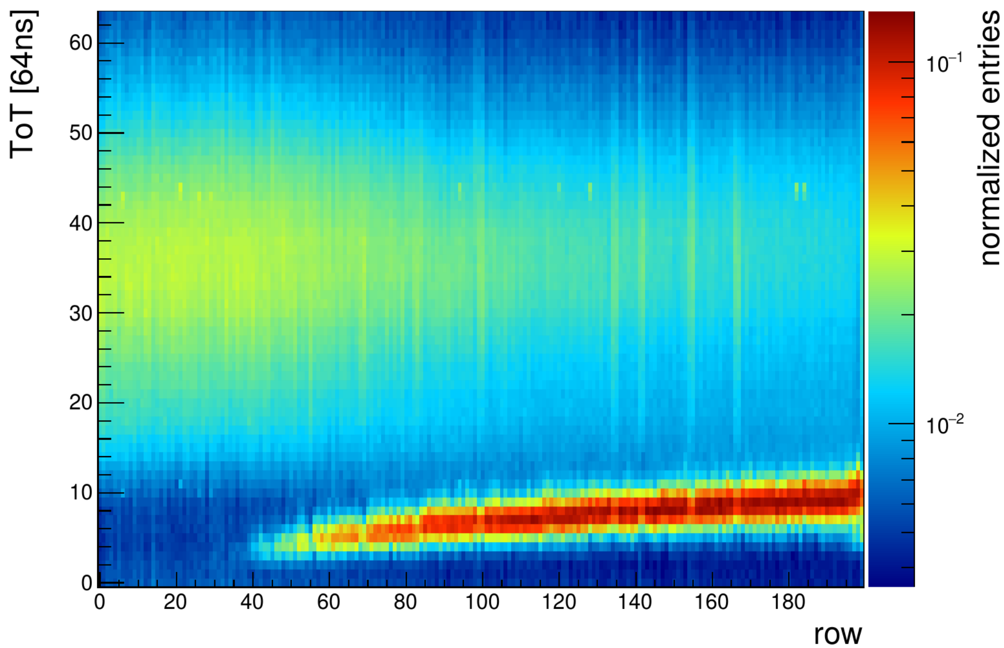
Problem:
→ capacitive coupling between RO lines

ATLASpix (discriminator in cell)
✔ binary(discriminated) RO

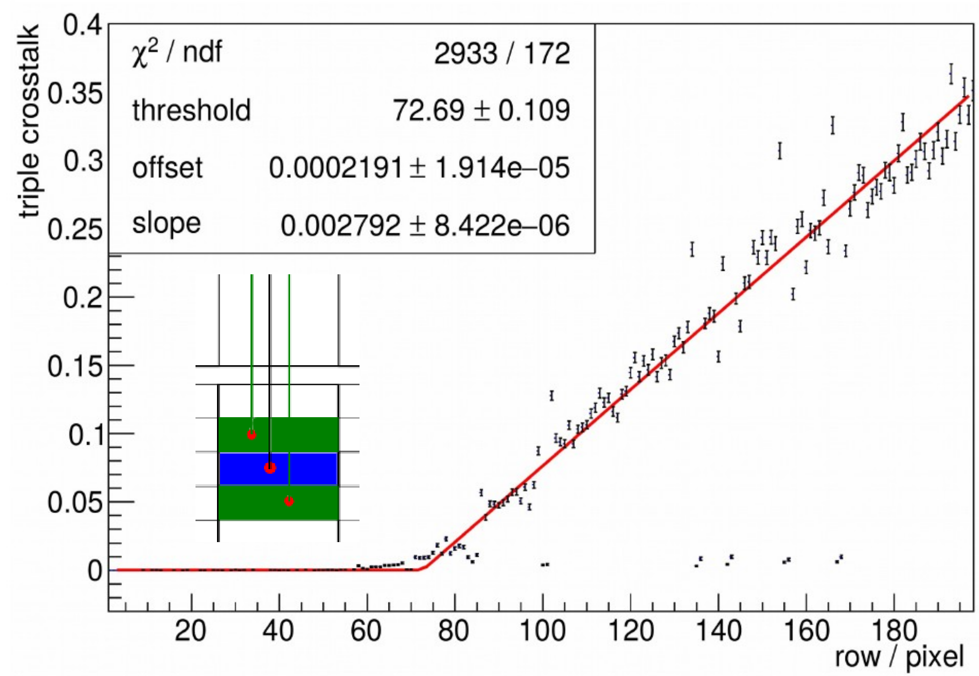
MuPix (analog amplified signal)
✗ source follower (A) → cross talk
✗ current driver (B+C) → in principle ok,
but design issues with Mupix8

Mupix8 Cross Talk (Source Follower)

Time over Threshold (dE/dx)



“Triplet” Probability

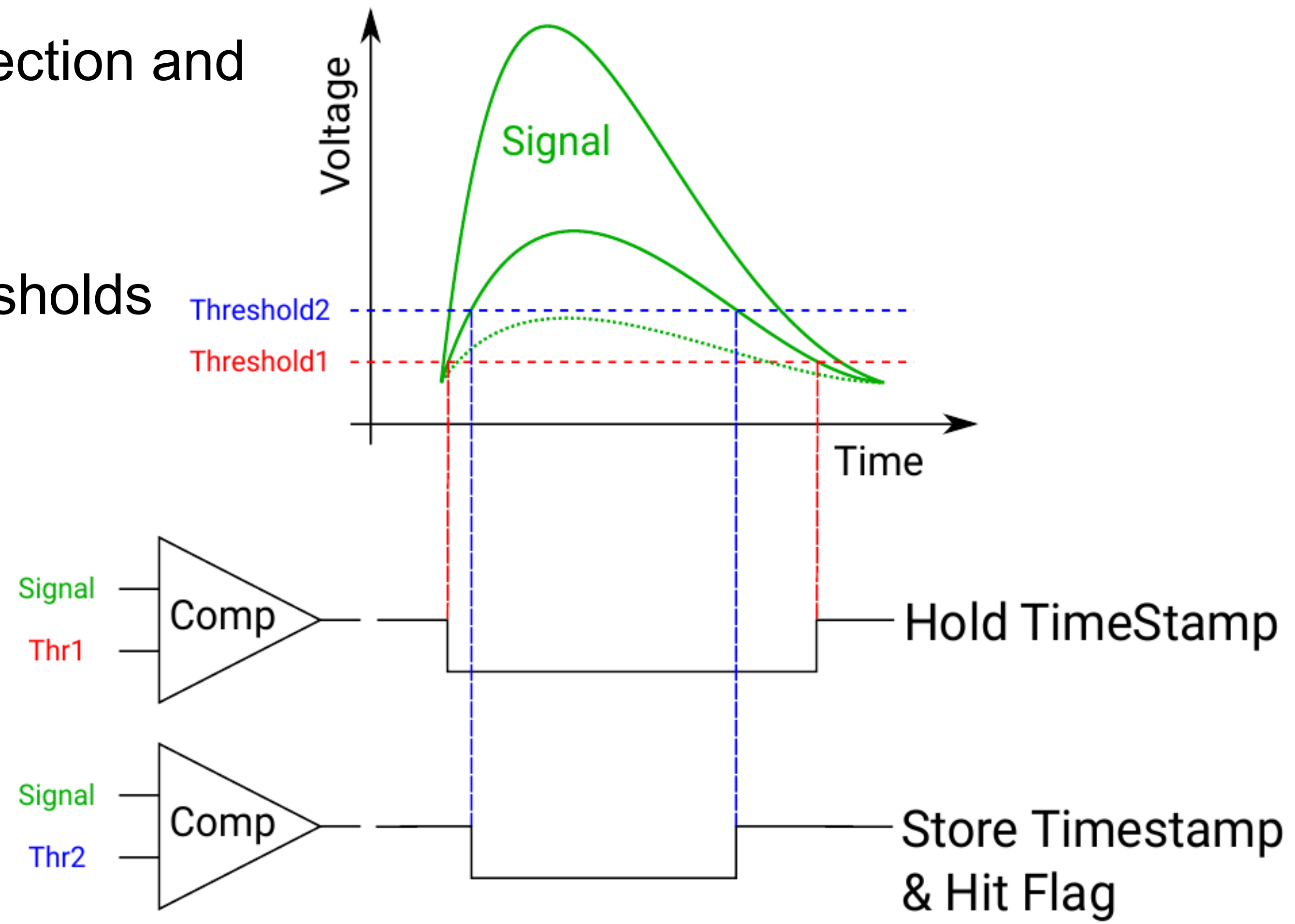


row number is proportional to length of trace!

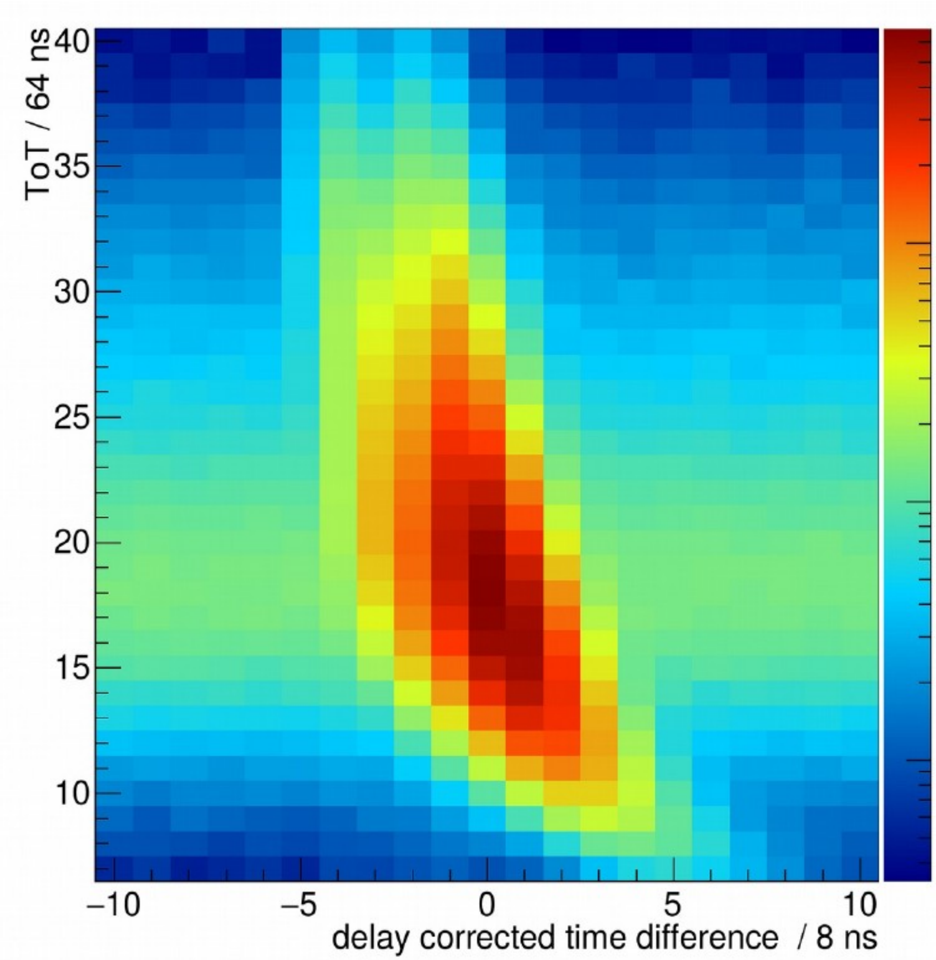
Mupix8: Time over Threshold and the 2-Discriminator Scheme

Methods for timewalk correction and mitigation:

- ToT correction
- sensing & validation thresholds
- combination



Mupix8: Timewalk Correction



"small signals come late..."

Good Correlation between ToT and hit delay time!

Mupix8 matrix A: Time Resolution Results

Time resolutions

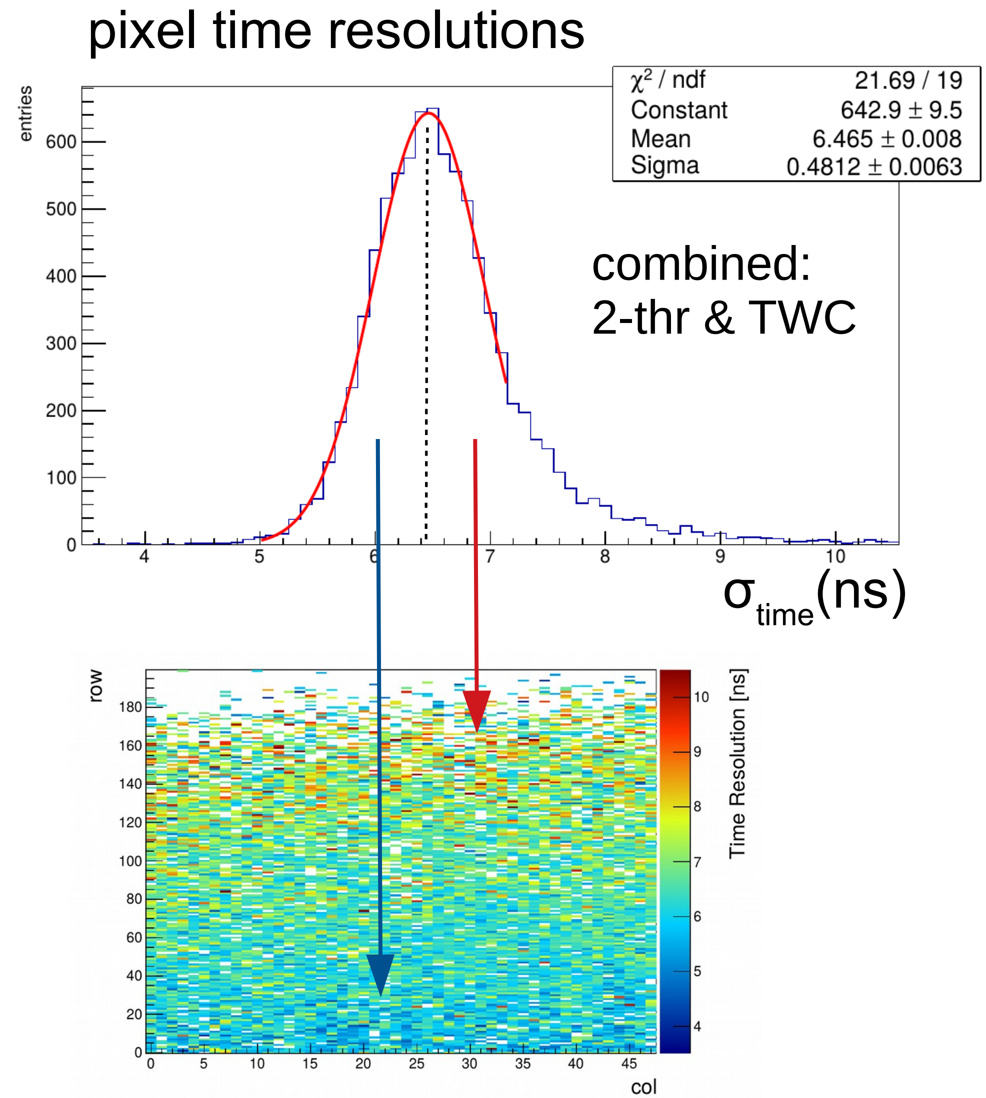
(of full matrix & after delay corrections)

σ=10.5 ns
(w/o correction)

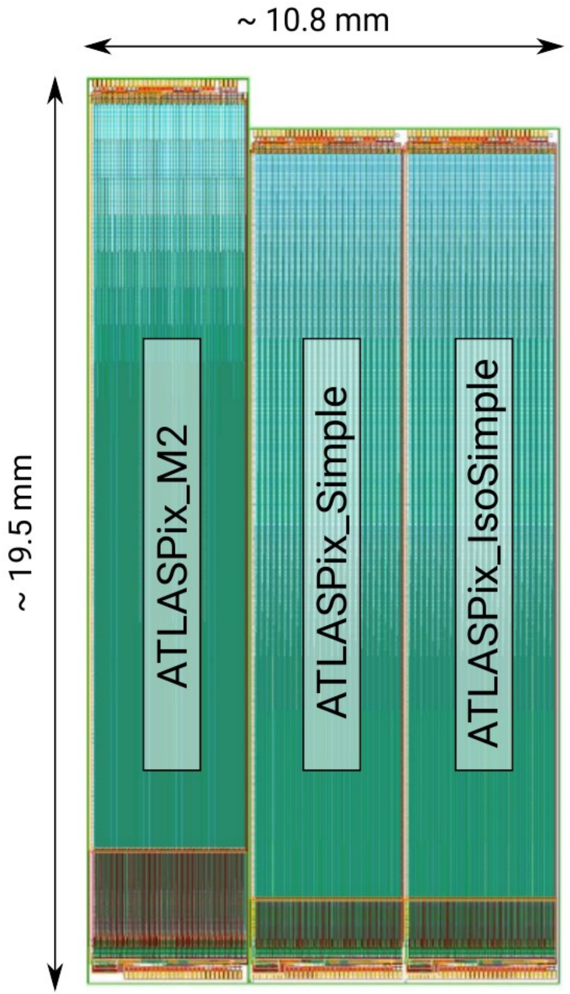
σ=7.6 ns
(timewalk corr.)

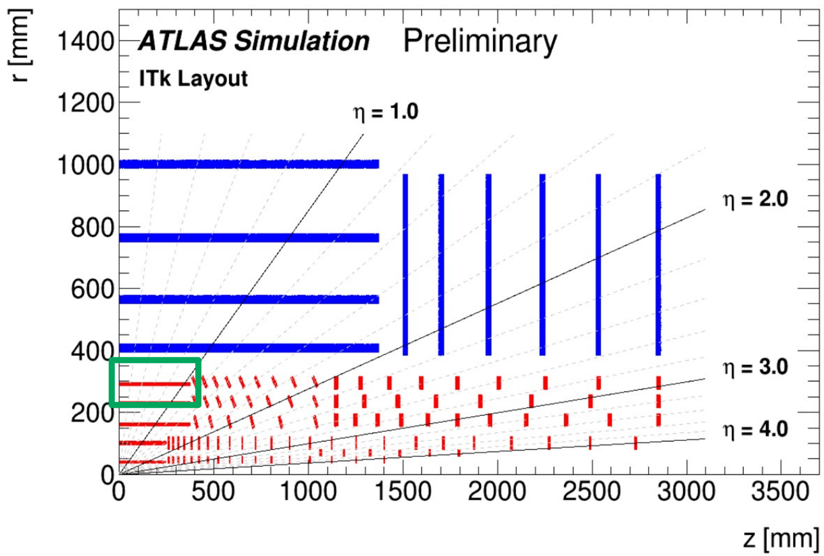
σ=8.8 ns
(2-threshold)

σ=6.5 ns
(combined)



ATLASpix

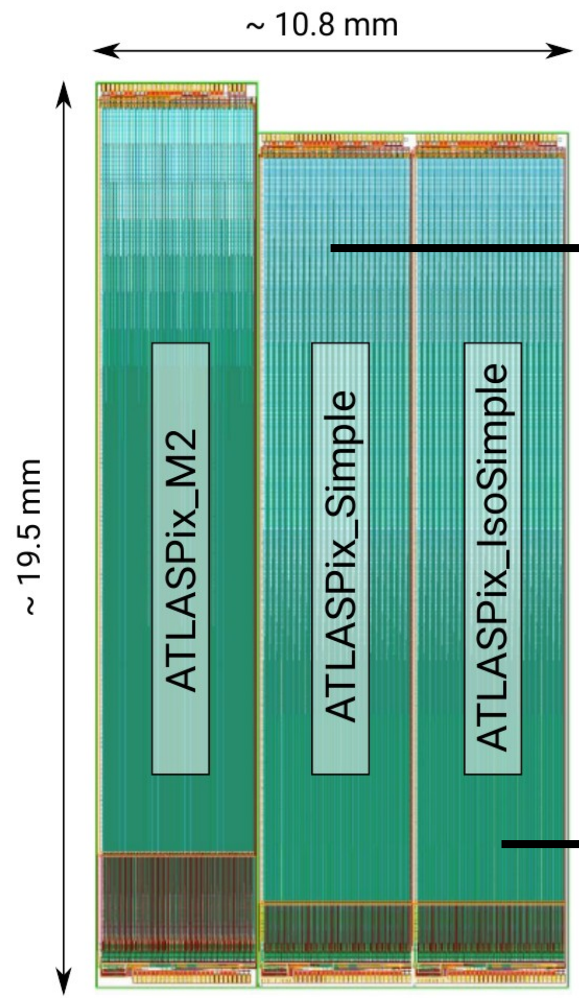


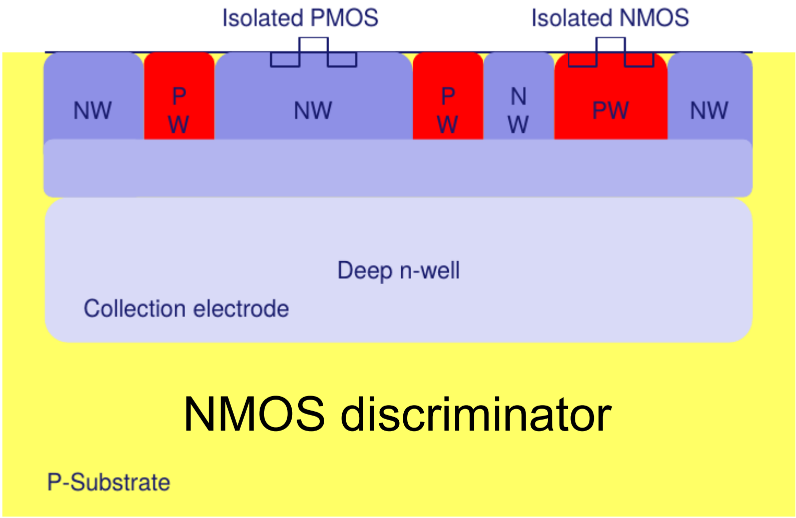


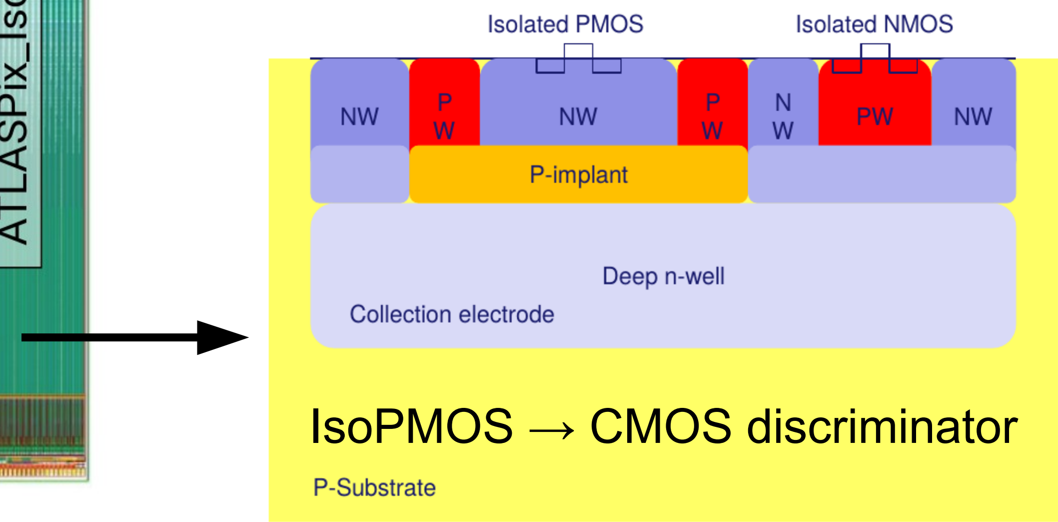
Goals

- HVMAPS demonstrator for ATLAS 4th pixel barrel layer
- compatible with ITK pixel (LHC) specification
- compatible with FE-I4 frontend chip
- **ATLASpix1** is a first **technology** demonstrator (no FE-I4 functionalities)

ATLASpix_simple

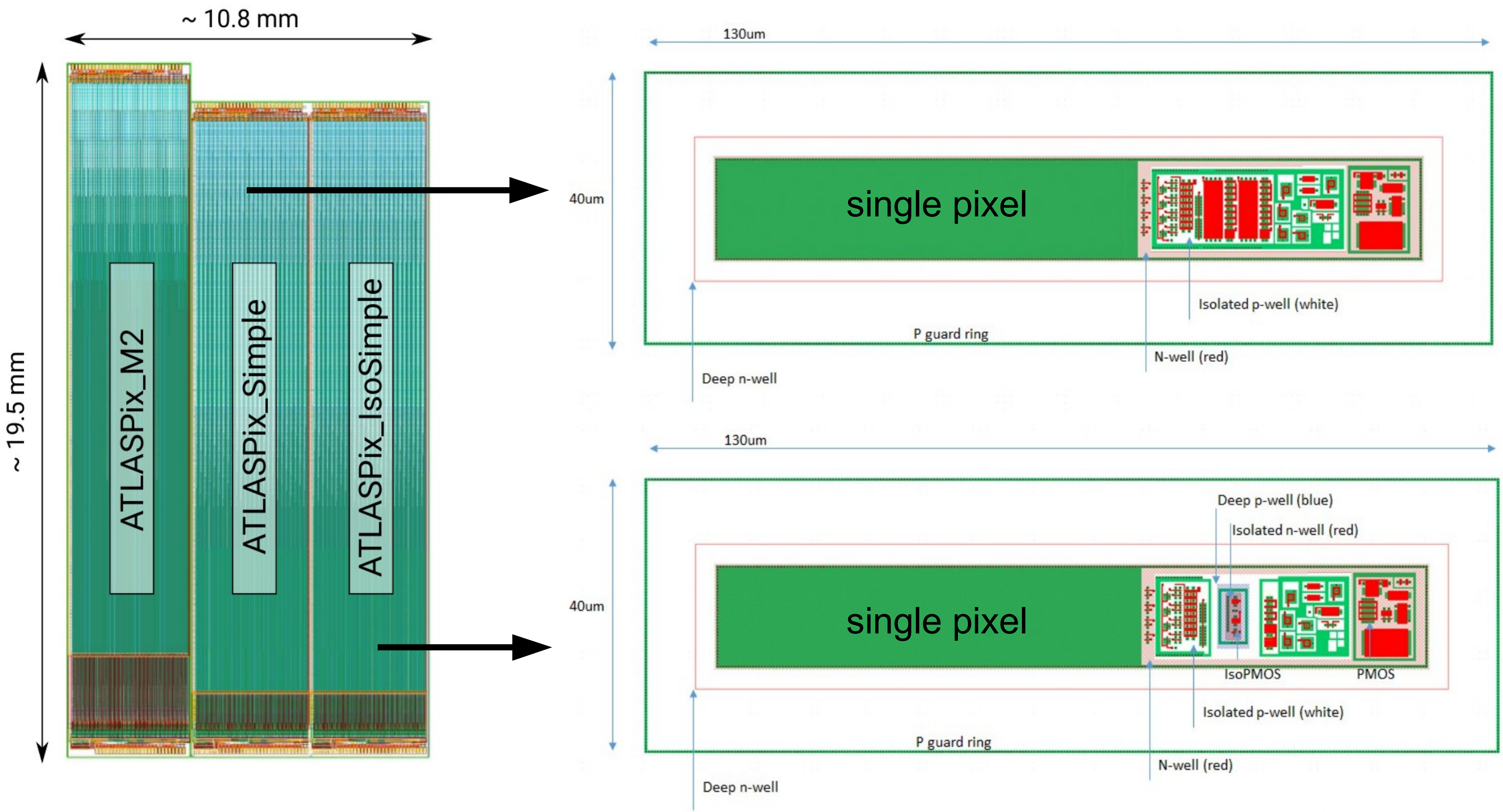






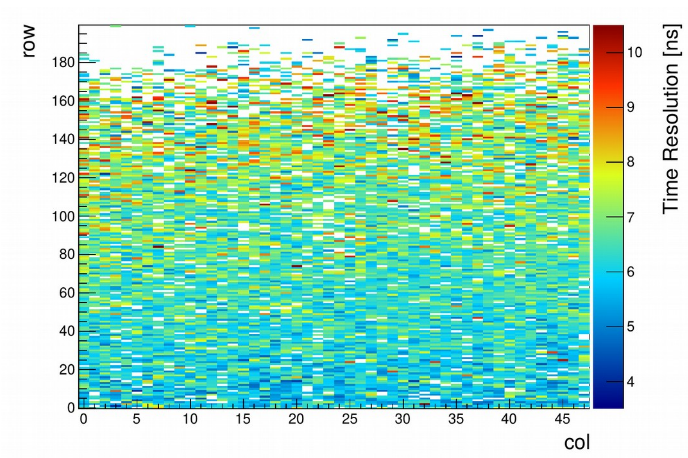
Note, discriminator is implemented in pixel!

ATLASpix_simple



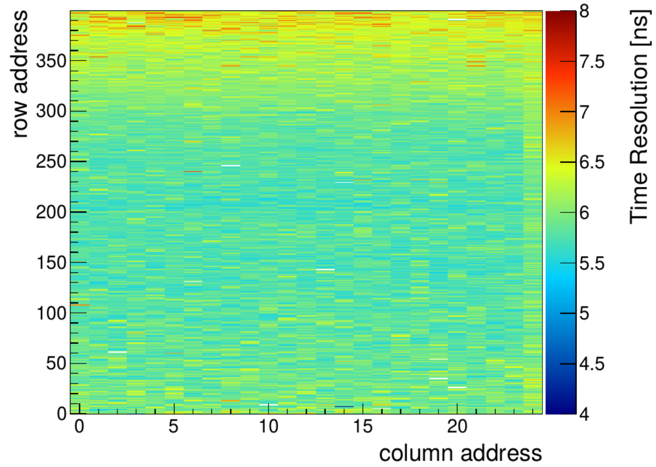
Time Resolution with and w/o TWC

MuPix8



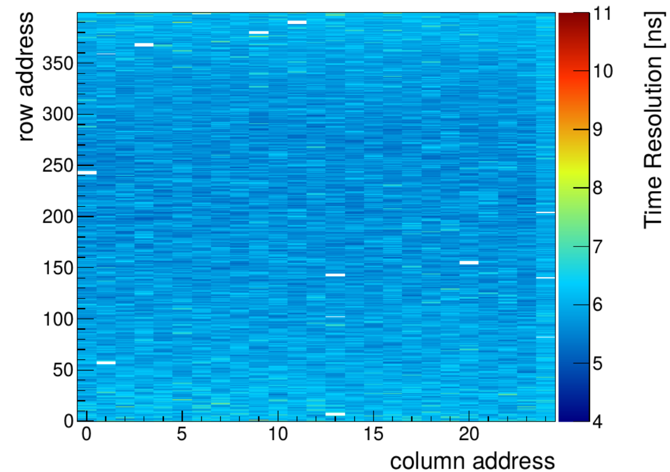
[sampling 8 ns]

ATLASpix_simple
(NMOS comparator)



[sampling 16 ns]

ATLASpix_simple_iso
(CMOS comparator)

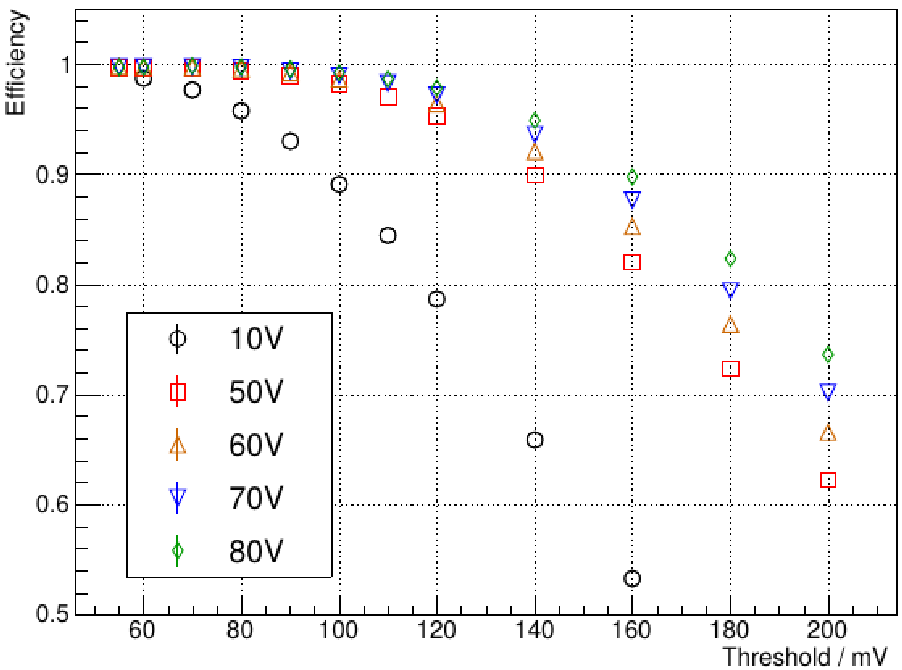


[sampling 16 ns]

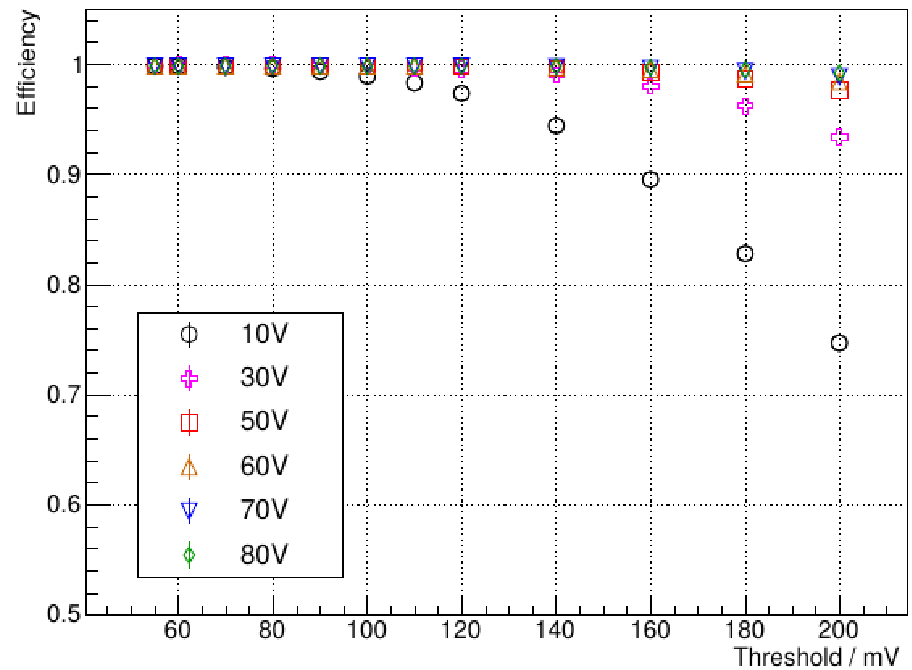
	MuPix8	ATLASpix_simple	ATLASpix_simple_iso
w/o TWC:	8.8 ns	8.1 ns	6.8 ns
with TWC:	6.5 ns (6.2 ns)	5.9 ns	5.8 ns
internal res.:	6.1 ns (5.8 ns) (short traces)	3.7 ns	3.6 ns

Substrate Resistivity Dependence ATLASpix1

80 Ω cm

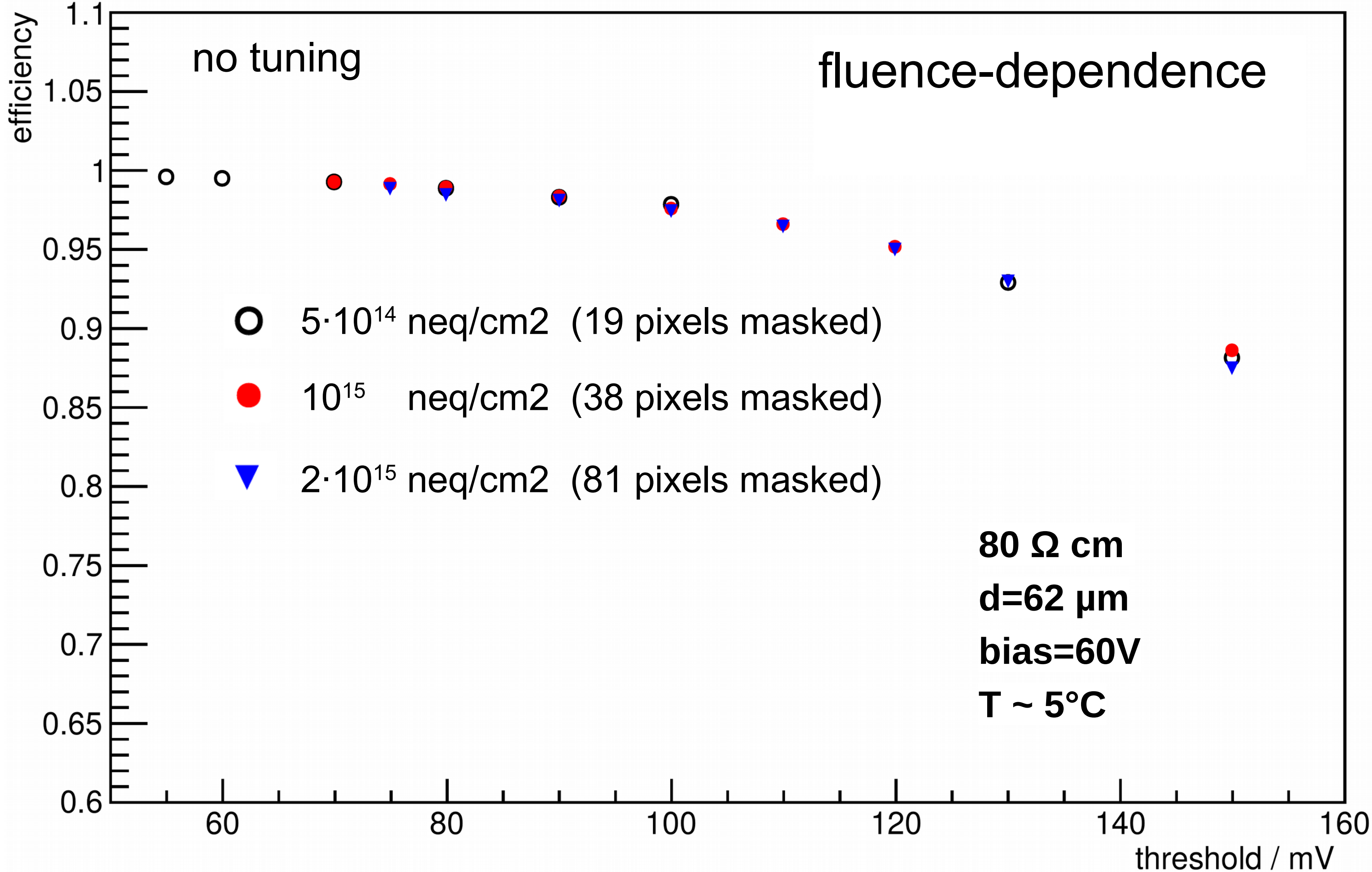


200 Ω cm



significant larger depletion with higher resistivity!

Neutron Irradiated 80 Ωcm ATLASpix1 @ 60V



Summary of Efficiencies after Irradiation

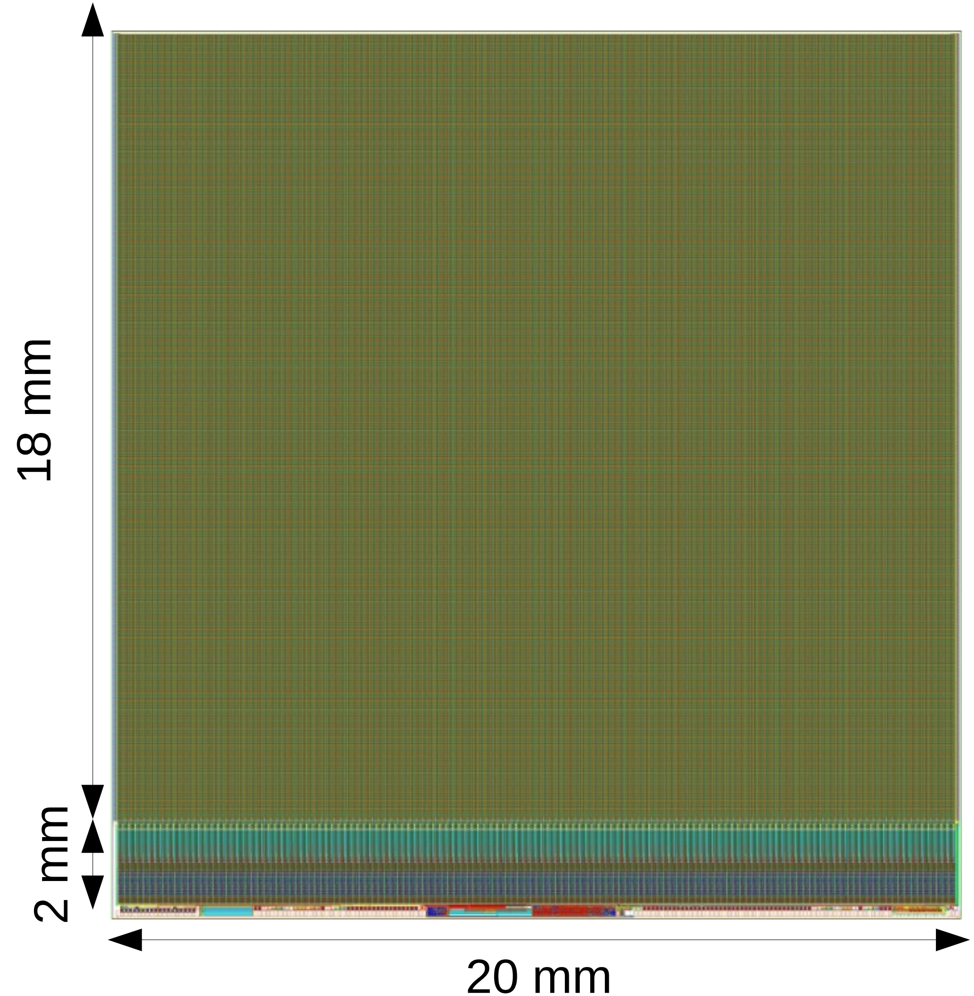
no tuning of pixels! ≤ 81/10000 pixel masked

Efficiency$_{40\ \mathrm{Hz}}$	**sub-strate**	**thick-ness**	**bias voltage (#masked pixel)**			
fluence (neq/cm^2)	**(Ω cm)**	**(µm)**	**60 V**	**70/75 V**	**80/85 V**	**90/95 V**
n 2e15	**80**	**62**	**98.5%**	**98.4%**	**98.6%**	
n 1e15	**80**	**62**	**99.3%**		**99.5%**	**99.5%**
n 5e14	**80**	**62**	**99.5%**			
n 2e15	**200**	**100**	**96.5%**		**98.7%**	**98.7%**
n 1e15	**200**	**100/725**	**98.7%**	**99.4%**	**99.5%**	**99.4%**
n 5e14	**200**	**100**	**99.2%**			
p 5e14	**200**	**100**	**≥ 99.6%**	**≥ 99.7%**	**≥ 99.9%**	
p 1e14 (10 MRad biased)	**200**	**725**	**≥ 99.7%**		≥ means that the 40 Hz/pixel average noise limit was not reached	

New ATLASpix3 (TSI)

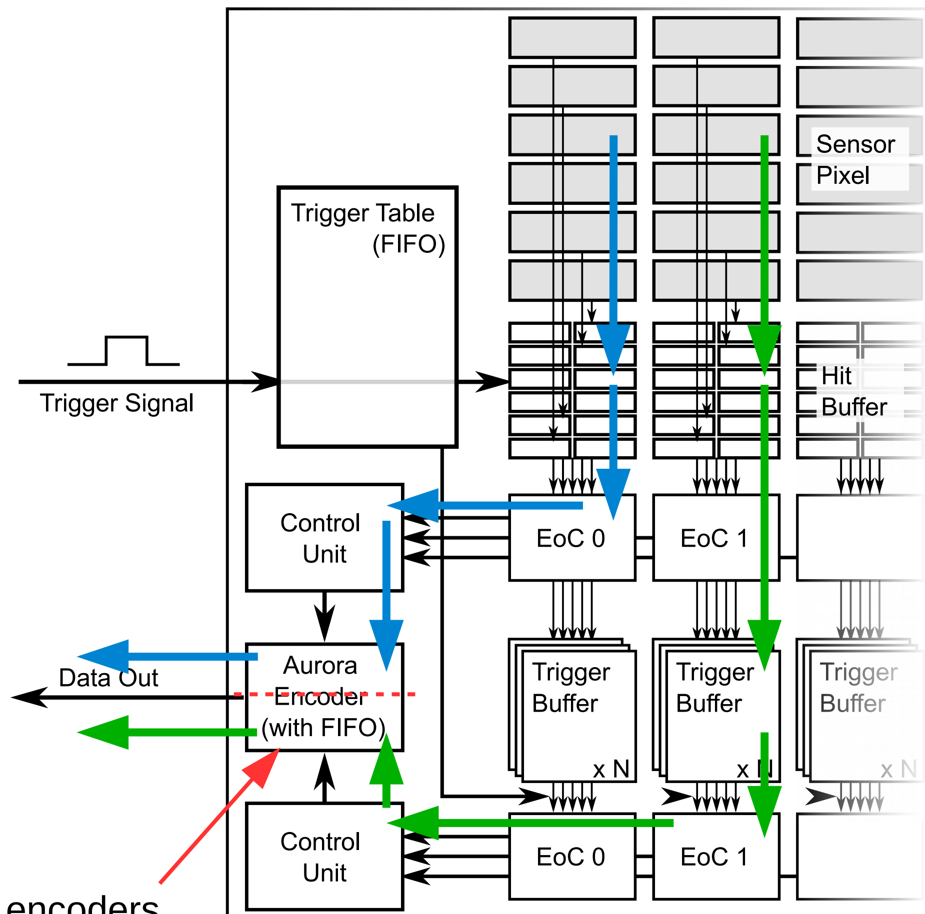
receivd in Sept. 2019

- Single matrix: 132 x 372 pixel
  - pixel size 150 x 50 μm²
- Column drain readout with and w/o trigger
- Radiation hard design with SEU tolerant global memory
- In-pixel comparator
- 64/66 bit Aurora encoder
- Command decoder with clock recovery
- prepared for serial powering (shunt LDOs)



ATLASpix3 – Readout Architecture

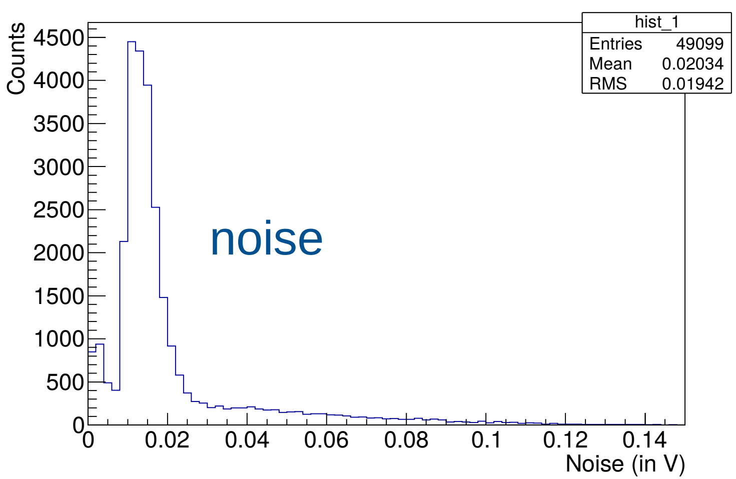
- Triggered and triggerless readout possible via two concurrent readout structures
    - separate control units
    - Configuration via SEU tolerant registers
- Data transmitted:
    - triggerless: 8/10b Aurora encoded
    - triggered: 64/66b Aurora encoded

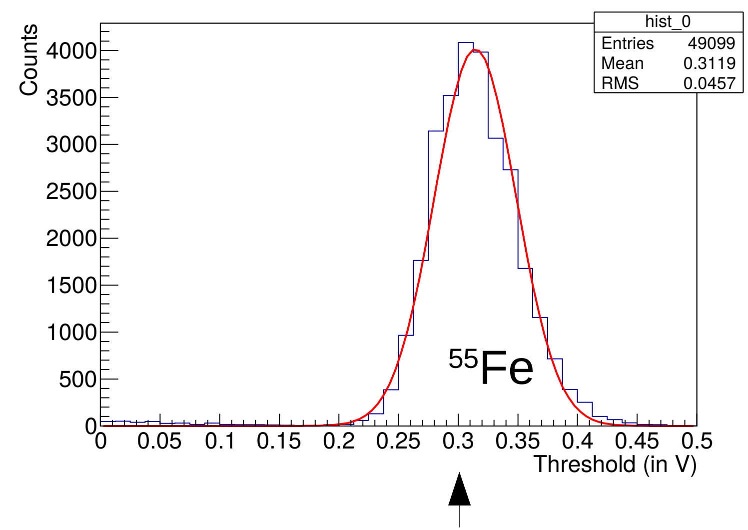


2 encoders,
triggered one with FIFO

ATLASpix3 - Threshold Distribution

- threshold scan for the whole matrix
- ^{55}Fe decay signals equal a charge injection of about 300 mV
- untuned matrix



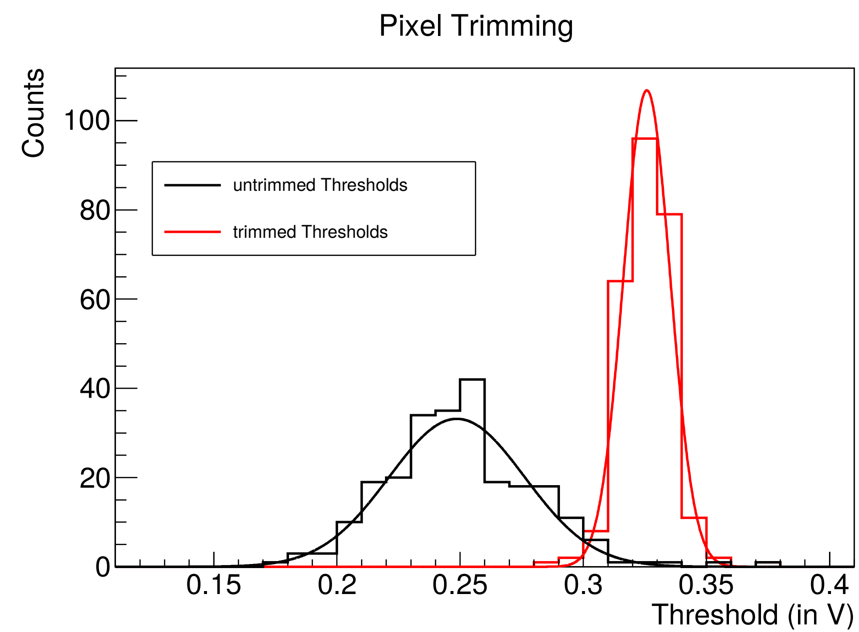


ATLASpix3 – Matrix Tuning

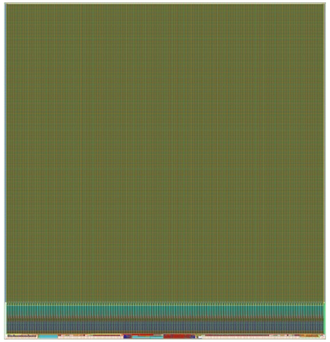
Threshold tuning:

- detection thresholds are adjusted to μ+3σ of untuned distribution
- conducted for two rows (in total 264 pixels):

$$\sigma_{trimmed} = 9.5\text{mV} \quad \leftrightarrow \quad \sim 50\ e^-$$



ATLASpix3 – Summary

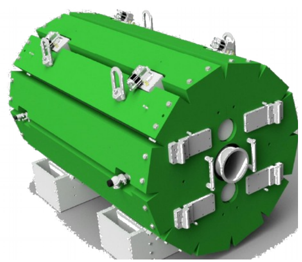


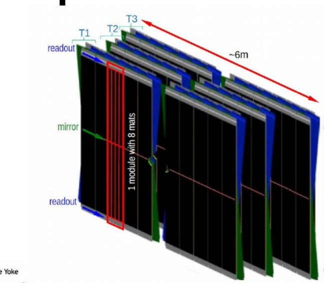
- ATLASpix3 is the first large (20 x 20 mm^2) HV-CMOS
  - high rate capable
  - radiation tolerant
  - triggered & untriggered RO
- ATLASpix3 seems to be fully operational

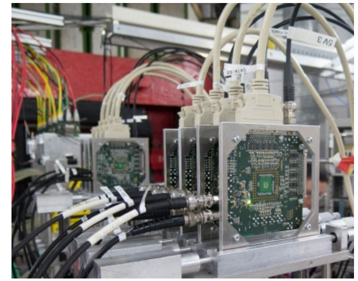
  → but more characterization studies required
- Unfortunately, CMOS option is no longer followed up for ATLAS-ITK
- However, ATLASpix3 is multi-purpose and serves as blueprint for
  - LHCb “Mighty Tracker” project
  - Telepix (beam telescope)

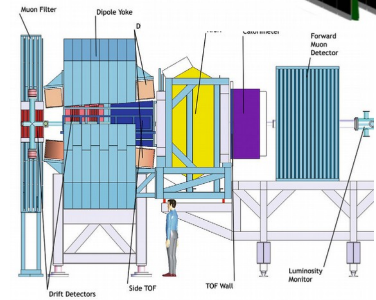
Conclusions & Outlook

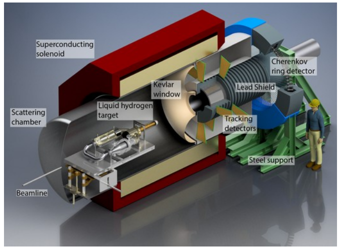
- HV-MAPS (ATLASpix, MuPix) is an established “technology” and have demonstrated their big potential
- Significant advances in ASIC design, also concerning system relevant aspects (e.g. configuration, regulators)
- HVMAPS are baseline for several projects/experiment:
  - Mu3e Phase I
  - LHCb Mighty Tracker
  - PANDA (Fair)
  - P2 at MESA (Mainz)
  - beam telescopes







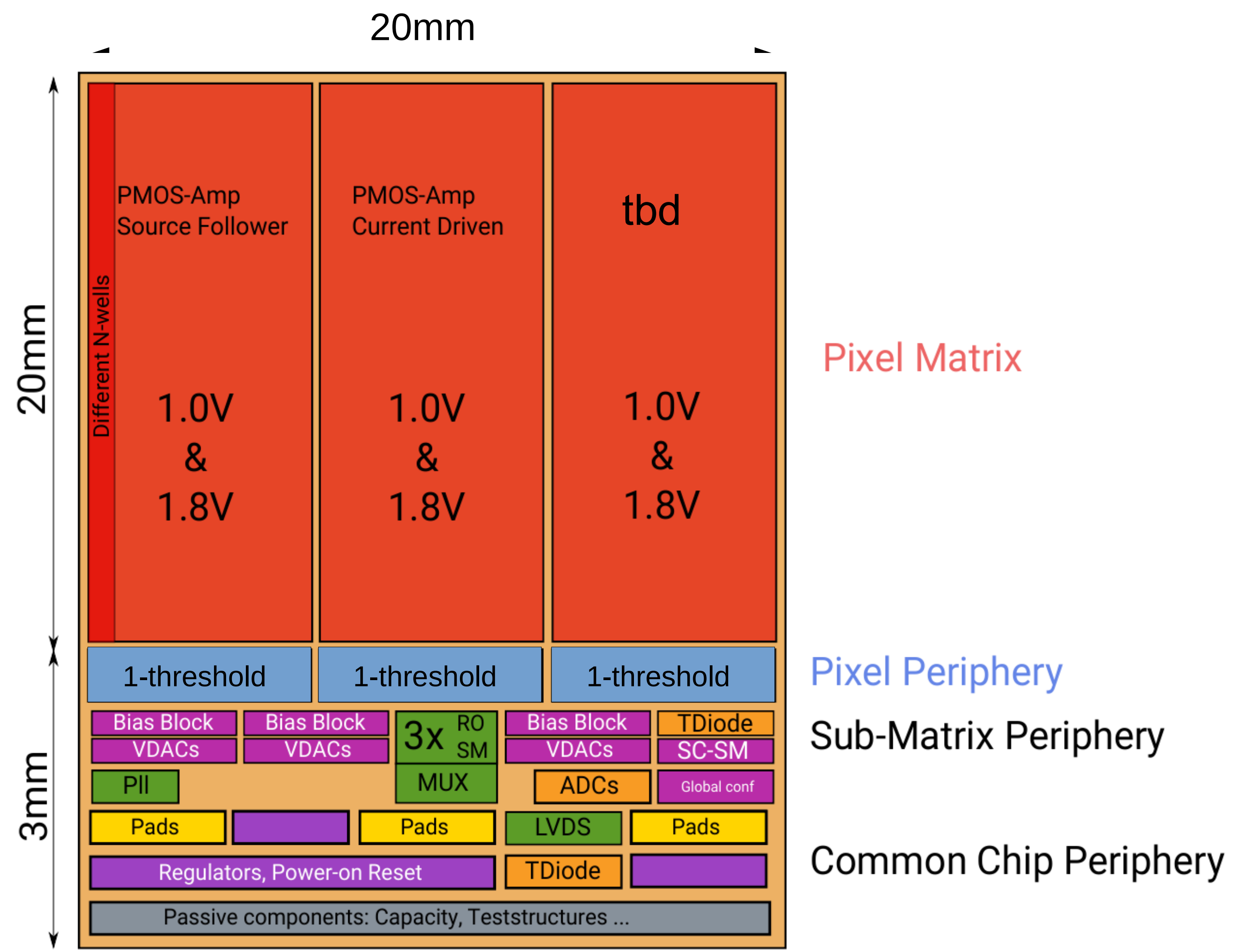




Mu3e Pre-to-Final HV-MAPS: Mupix10

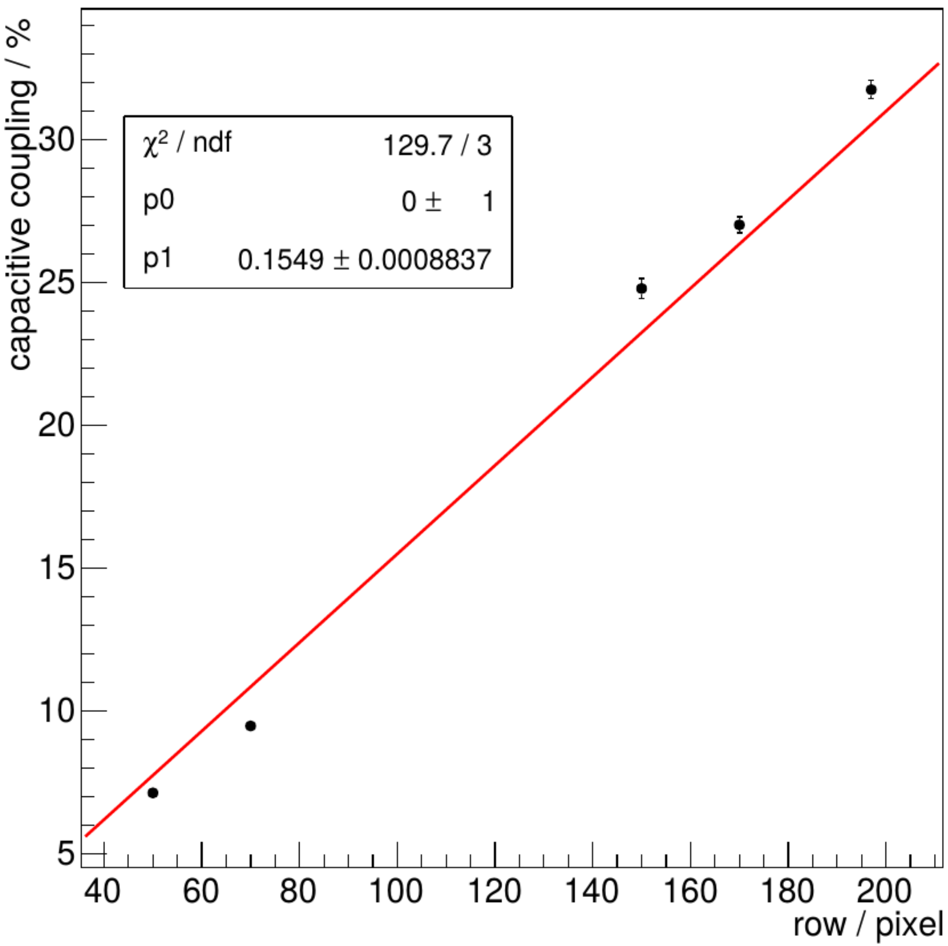
figure
not to scale!

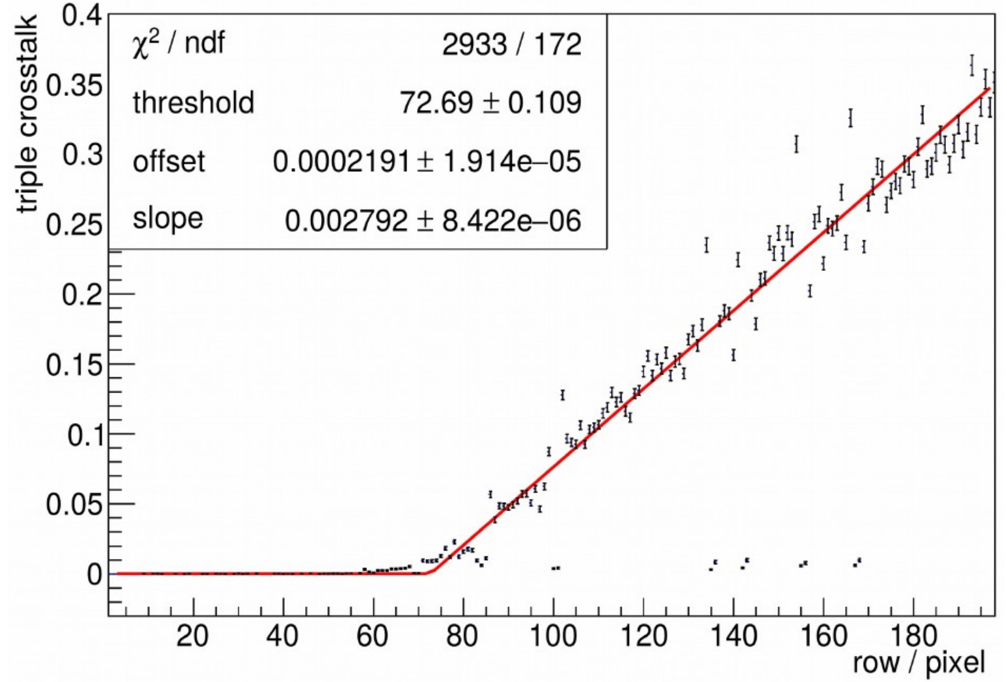
submission
in Nov. 2019



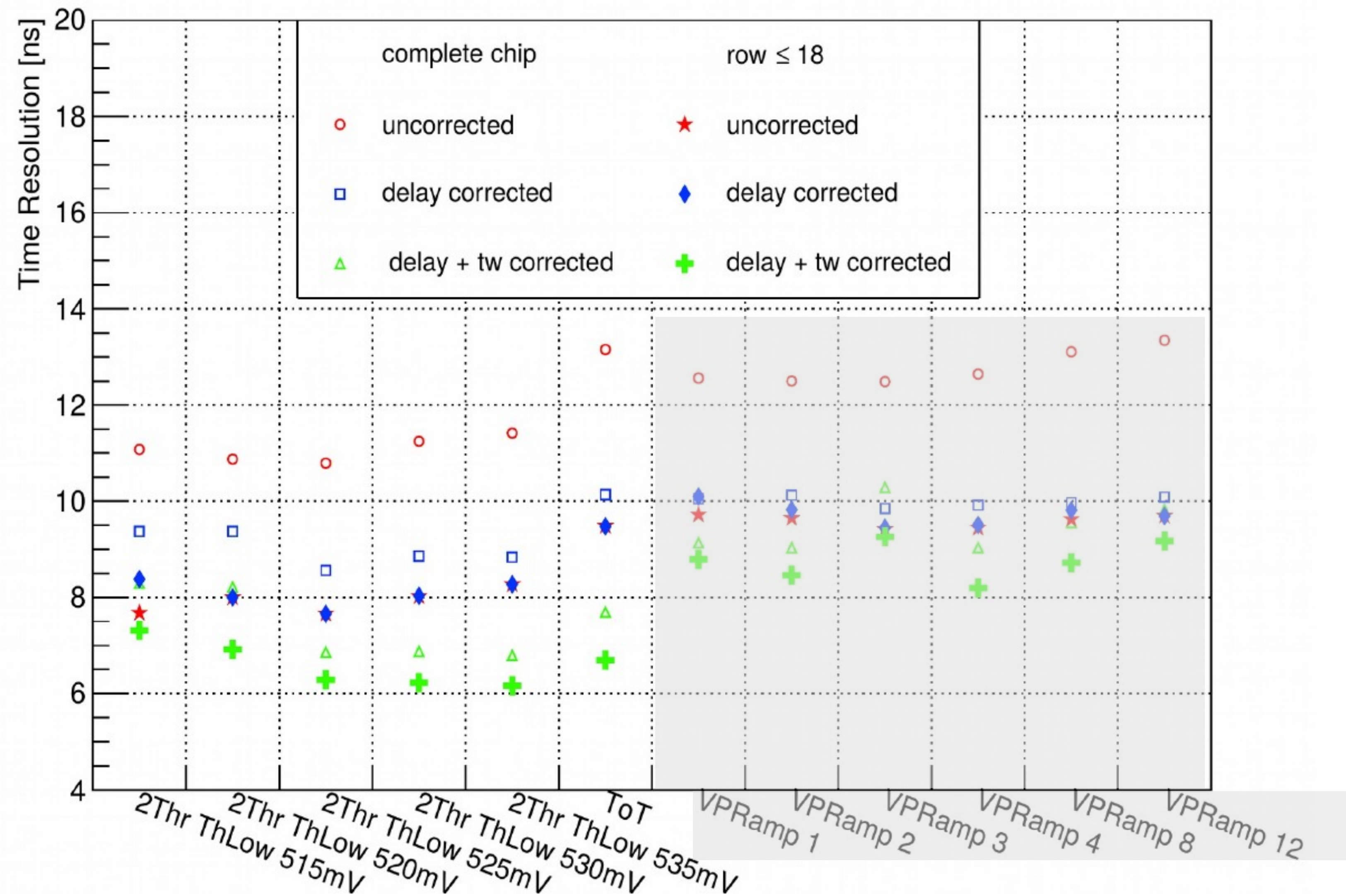
Backup

Mupix8 Cross Talk (Source Follower)

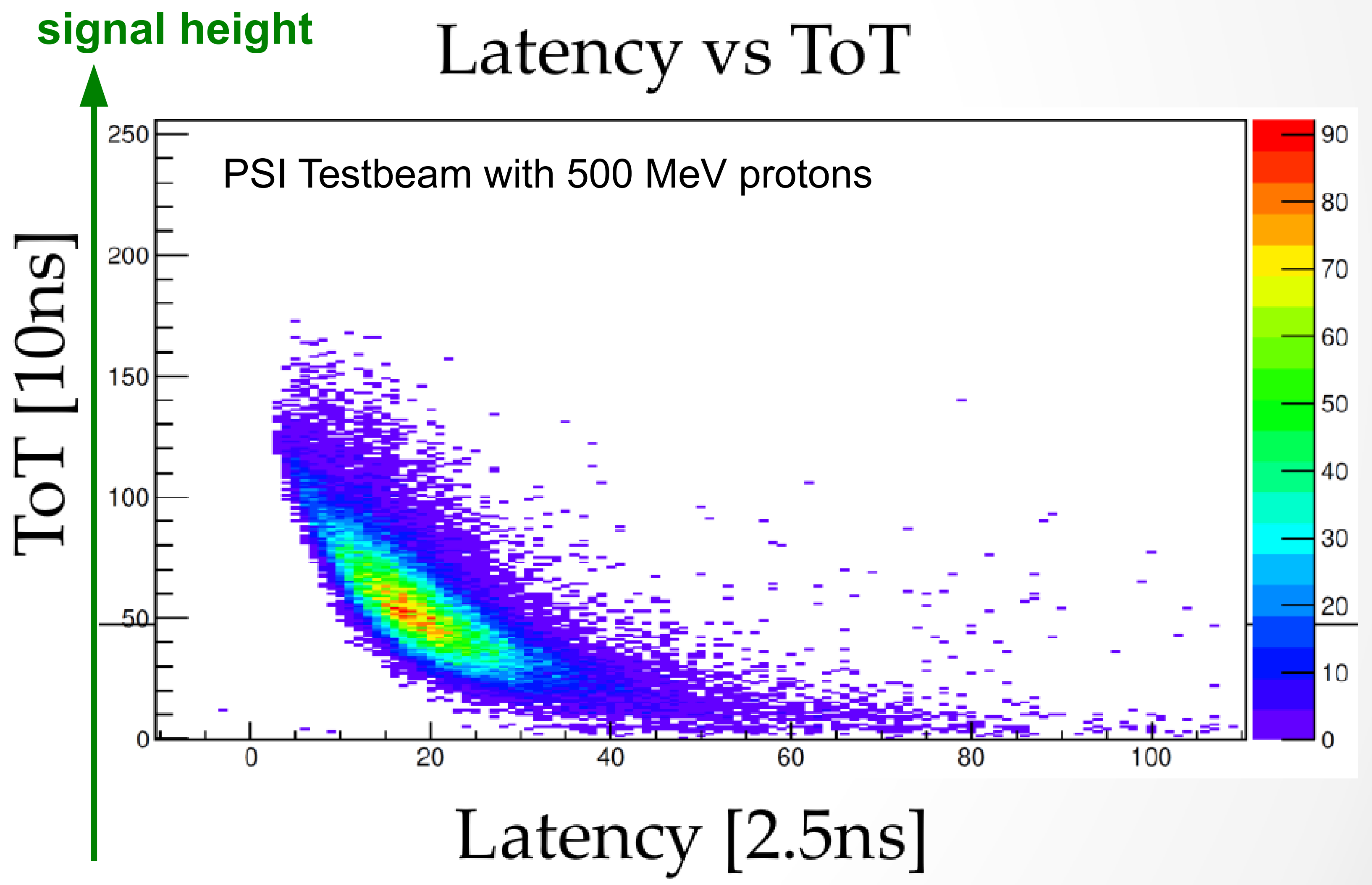




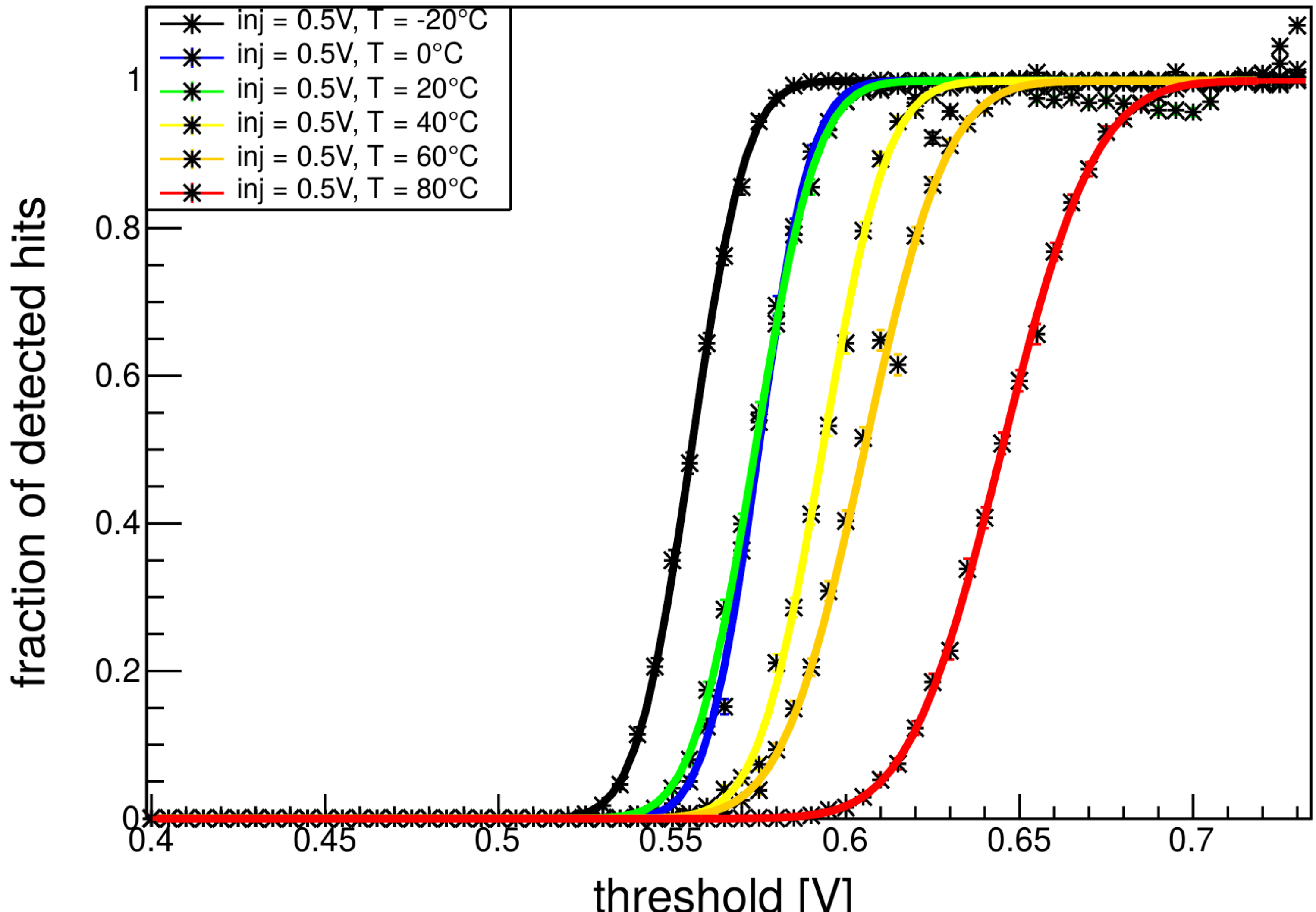
Mupix8: Time Resolution Results



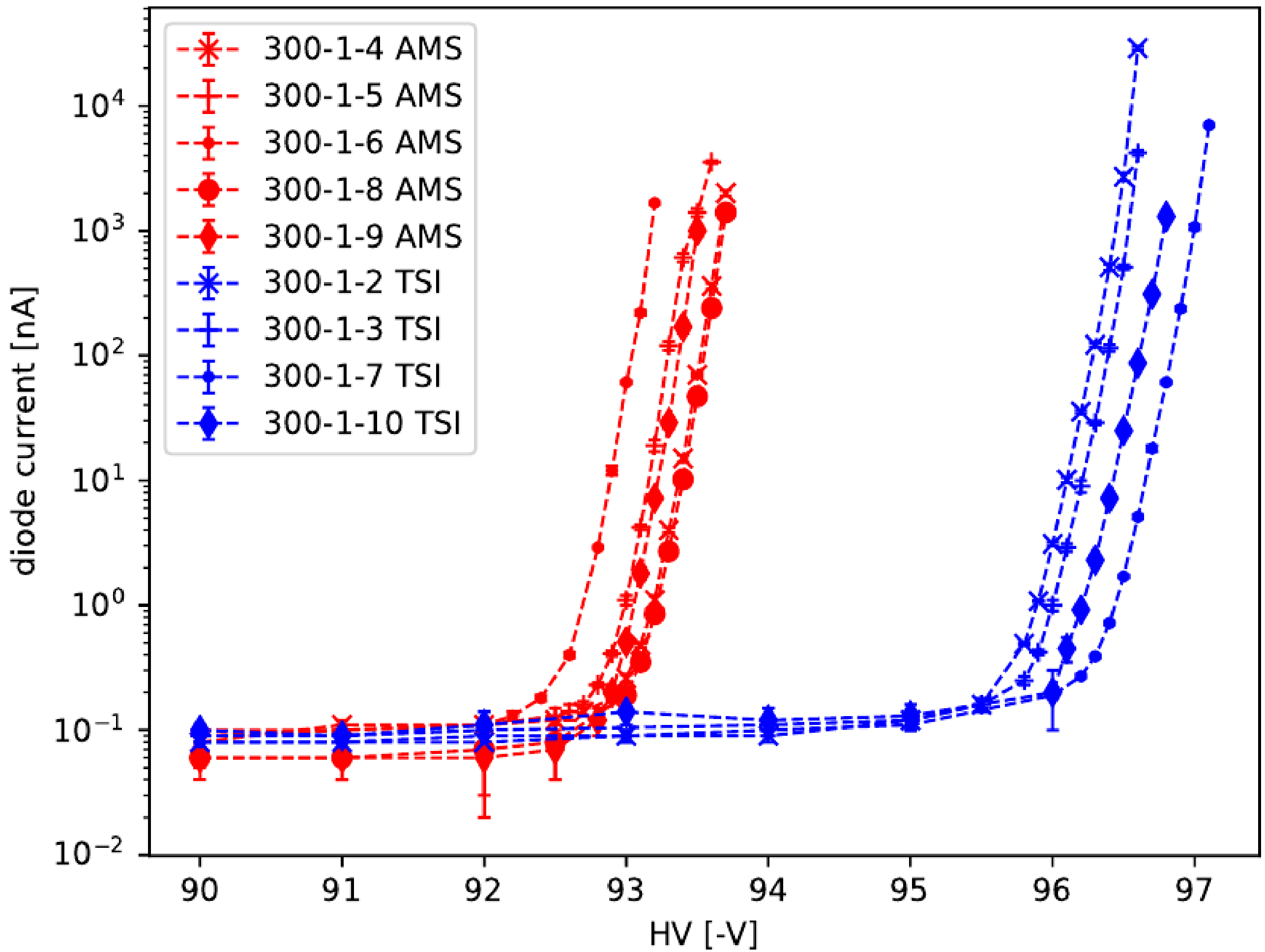
MuPix7 Time Resolution



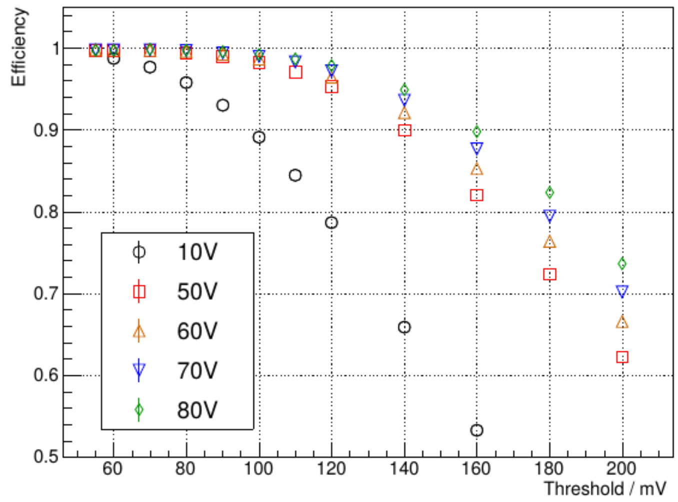
Mupix8: Temperature Dependence

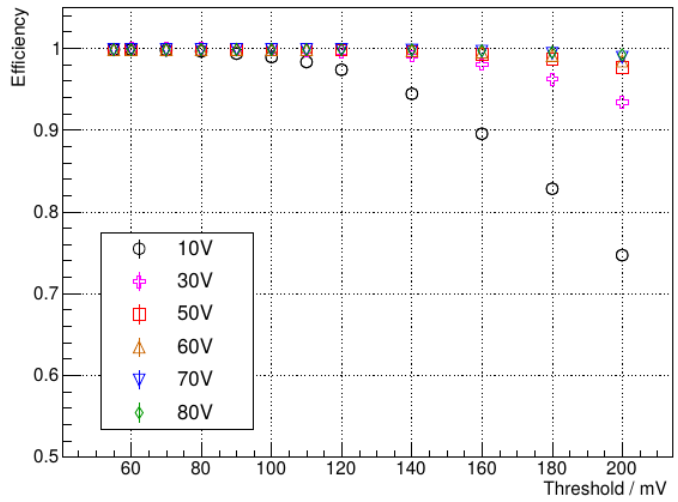


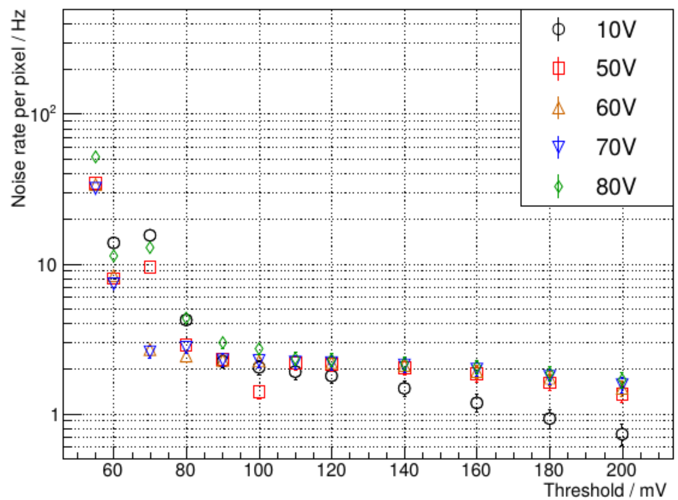
Mupix7 Breakdown Voltage: AMS H18 versus TSI H18

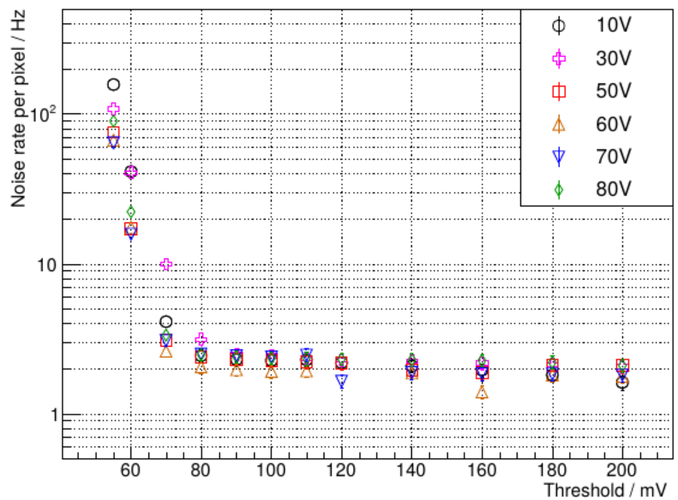


Substrate Resistivity Dependence

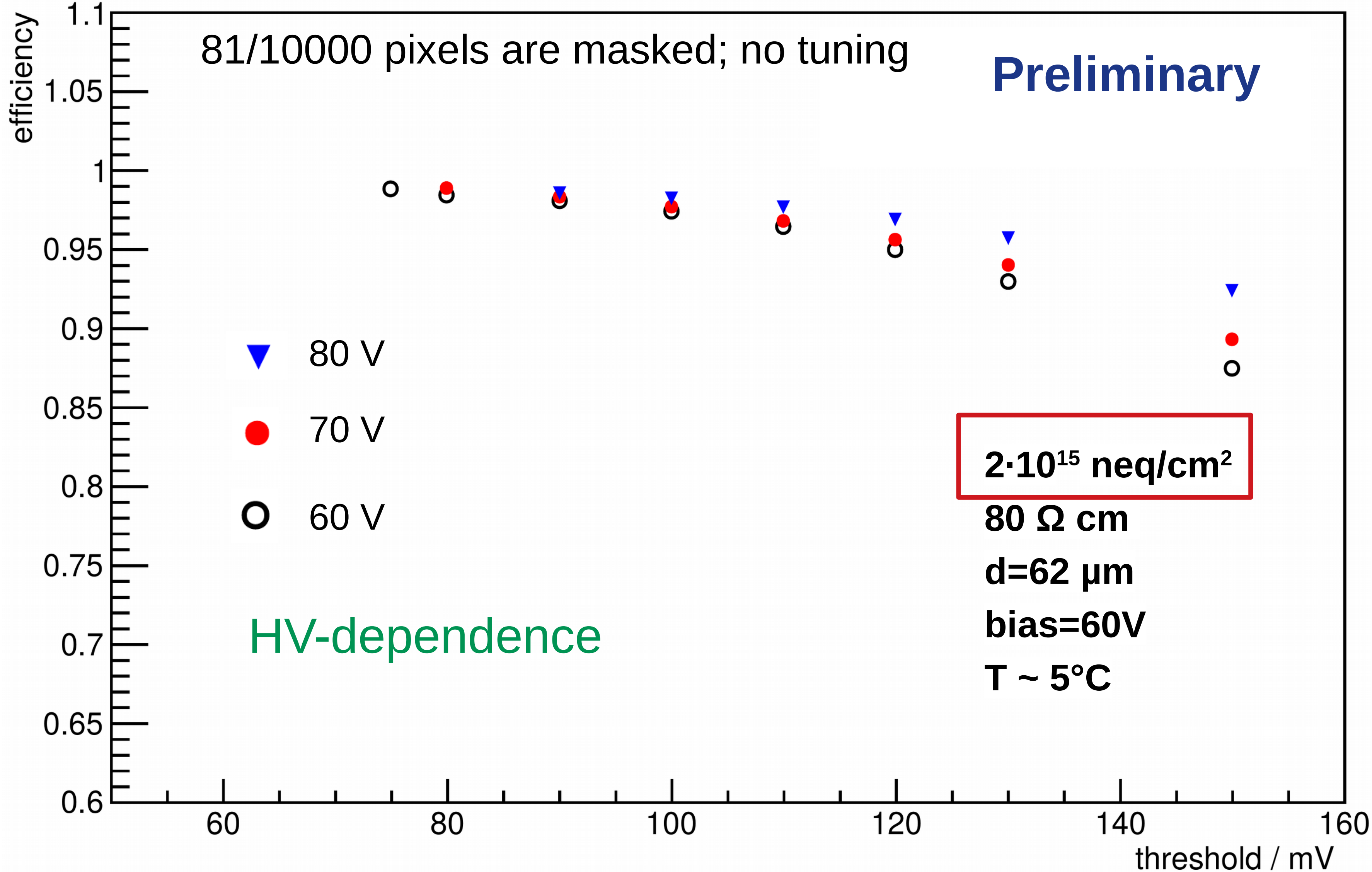








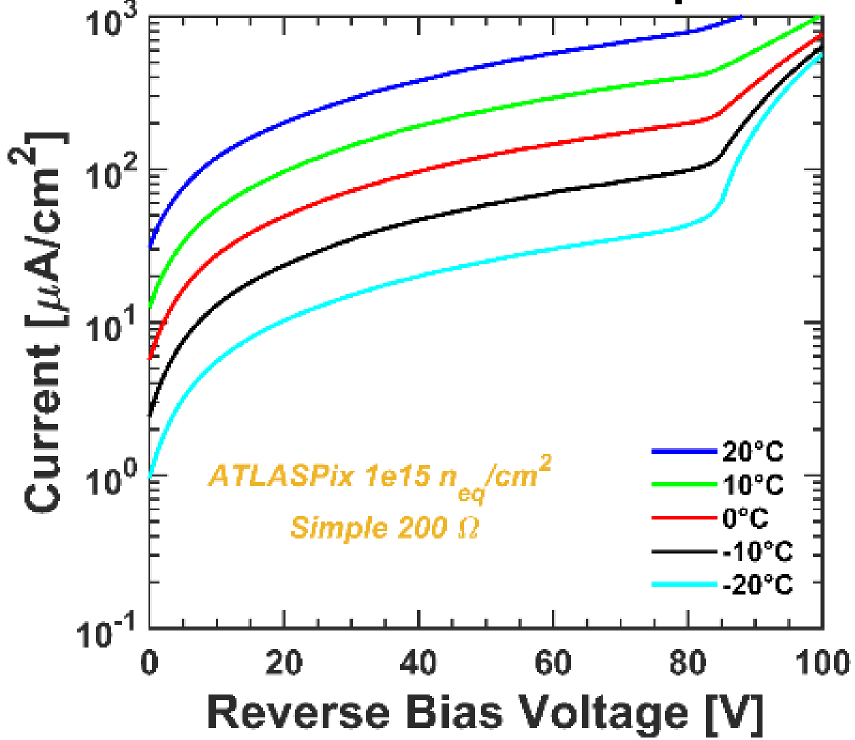
Neutron Irrad. 80 Ωcm Sensor @ 2e15 neq



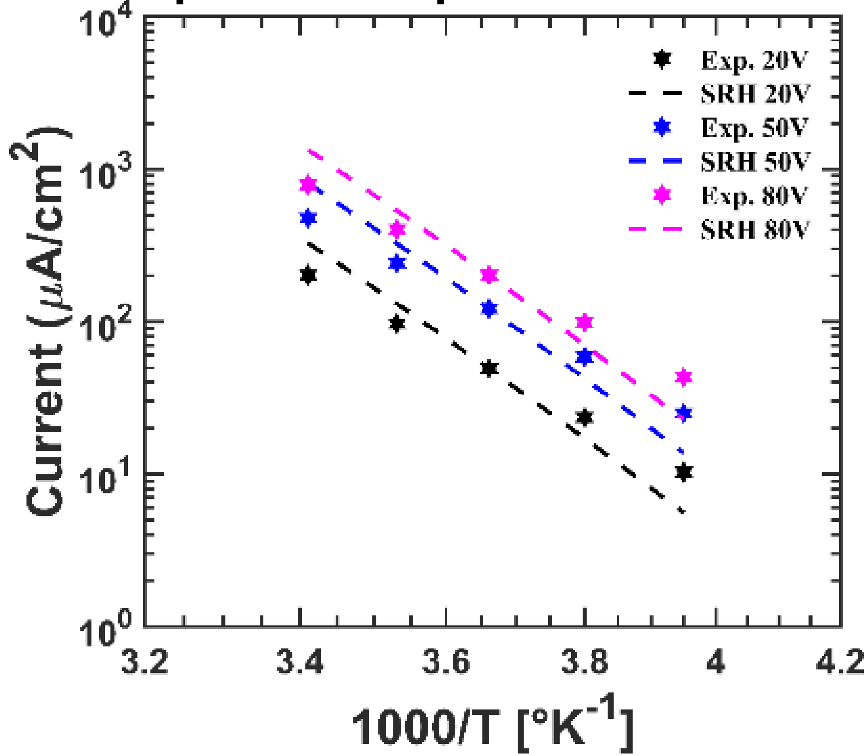
Leakage Currents: **200 Ω·cm (16.7 MeV p) 1e15 neq/cm²**

Irradiation campaign with 16.7 MeV protons at BERN with fluence 10^{15} neq/cm²

I-V Curves for different temperatures



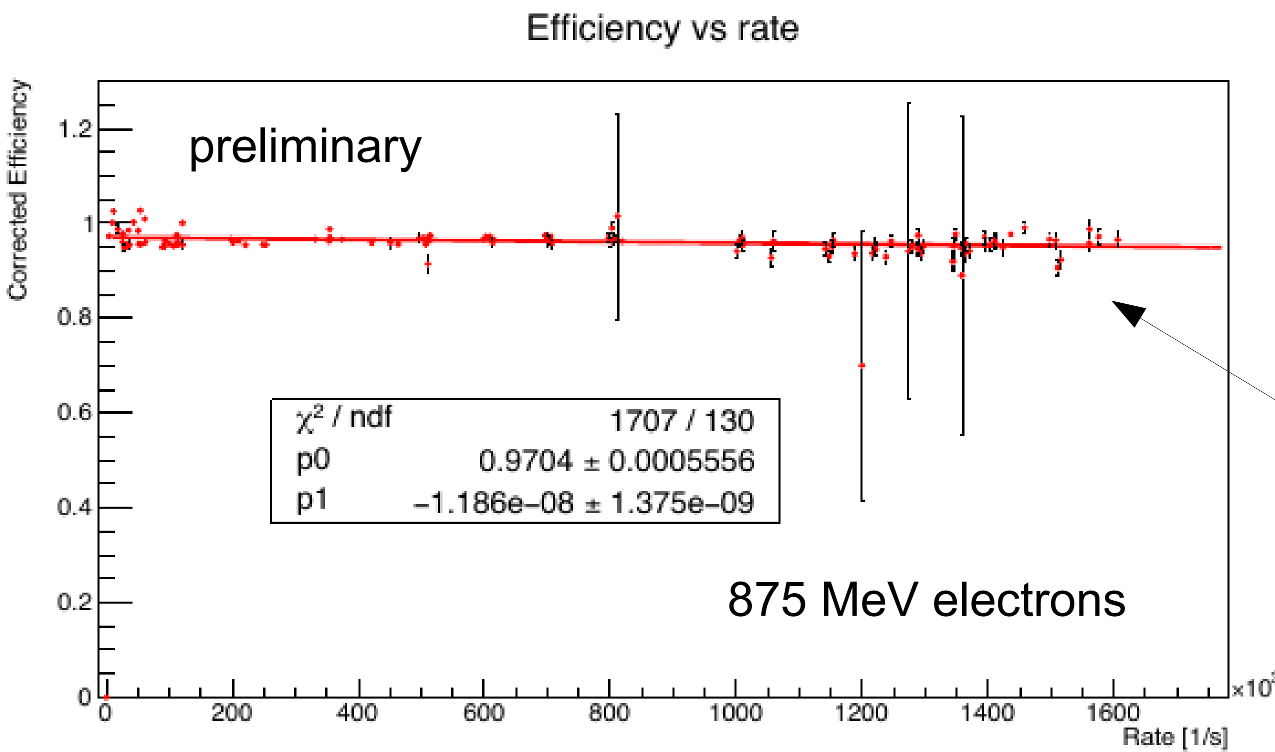
temperature dependence

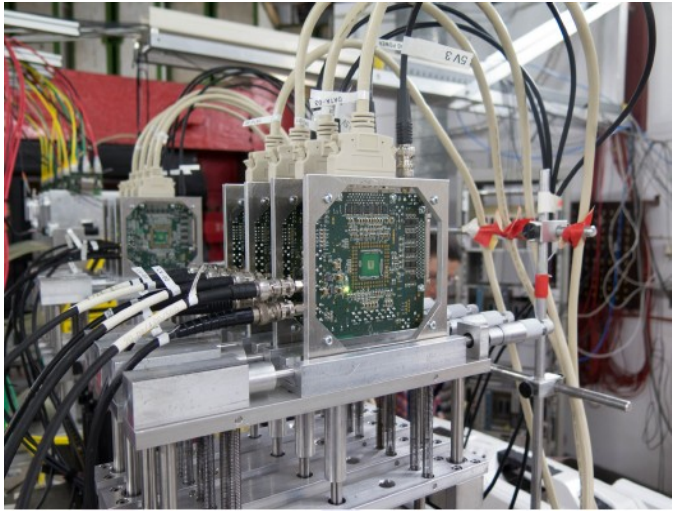


- leakage currents well below **50 μA/cm²** for temperature **T=-20°C** up to breakdown
- breakdown voltages increase with irradiation (not shown)
- Arrhenius prediction approximately holds for irradiated sensors
- similar studies for neutrons and for fluences up to 2e15 neq/cm²

MuPix Telescopes + Rate Tests

Rate test at MAMI:





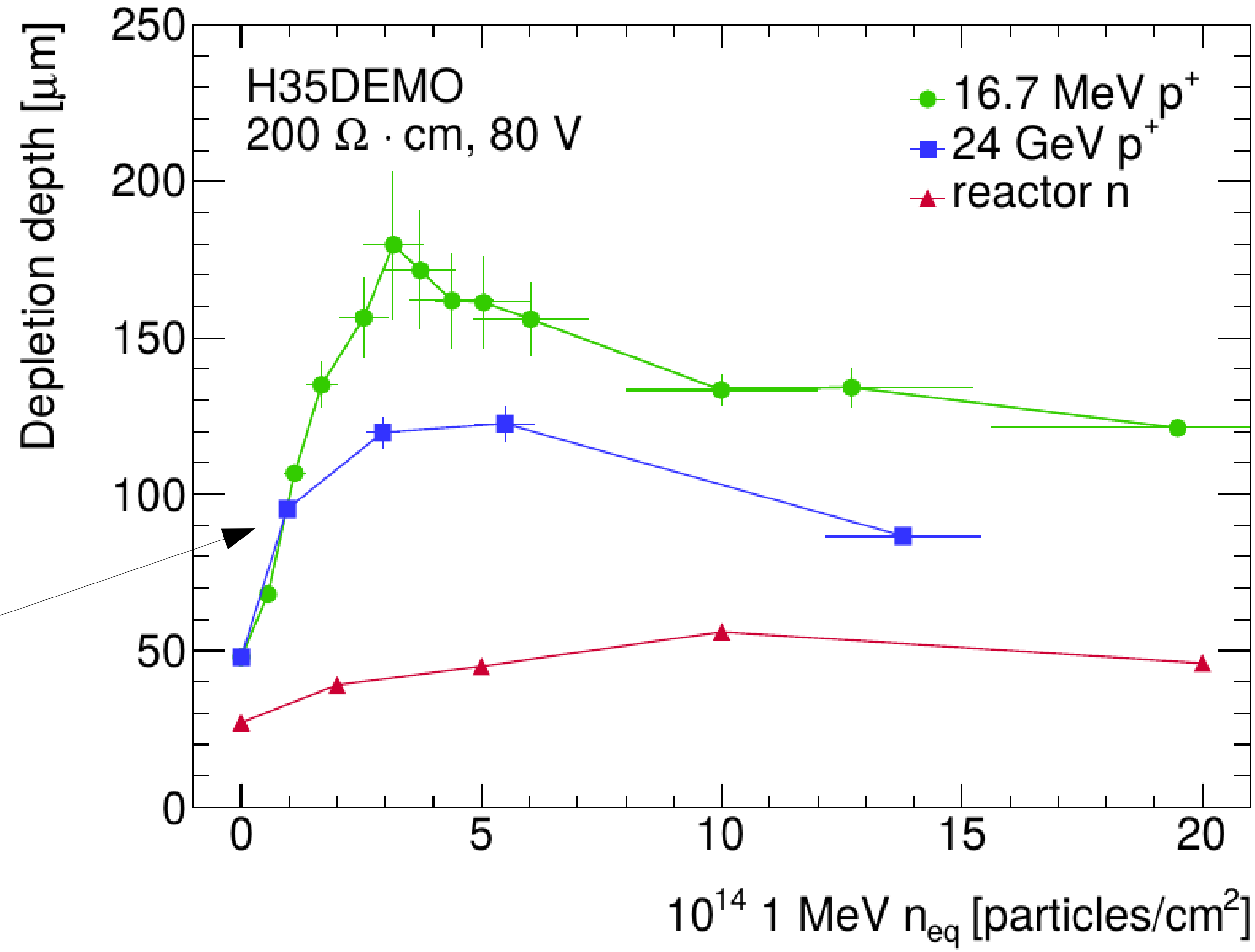
→ **very small rate dependence of efficiency!**

<u>MAMI rate test</u>

- **875 MeV e^-**
- maximum rate rate of **1.6 MHz / 5x5 pixels**
- corresponds to **780 Mhits/cm²/s**

Effect of Irradation on H35 process

arXiv:18007.09553

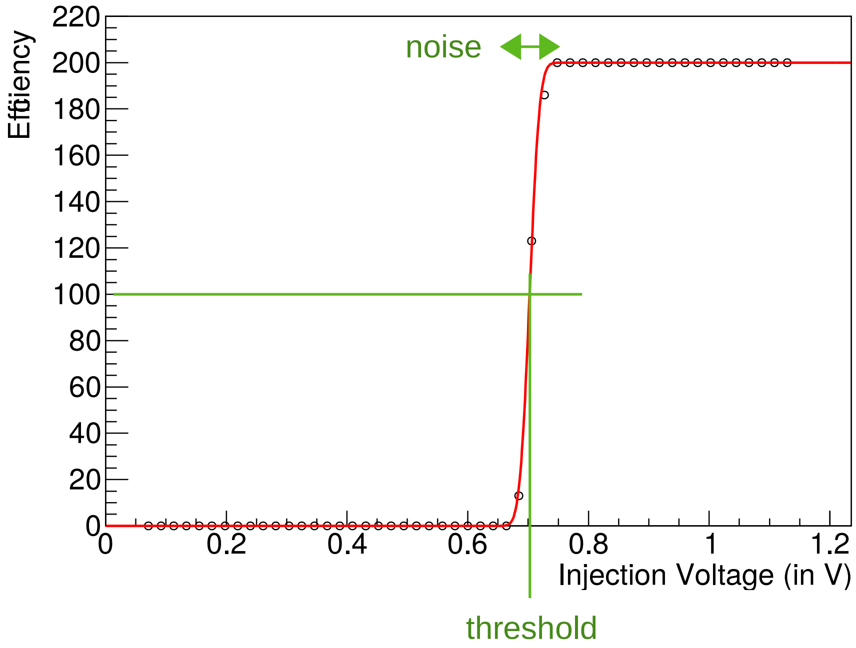


increase due to
acceptor removal

Threshold and Noise Definitions

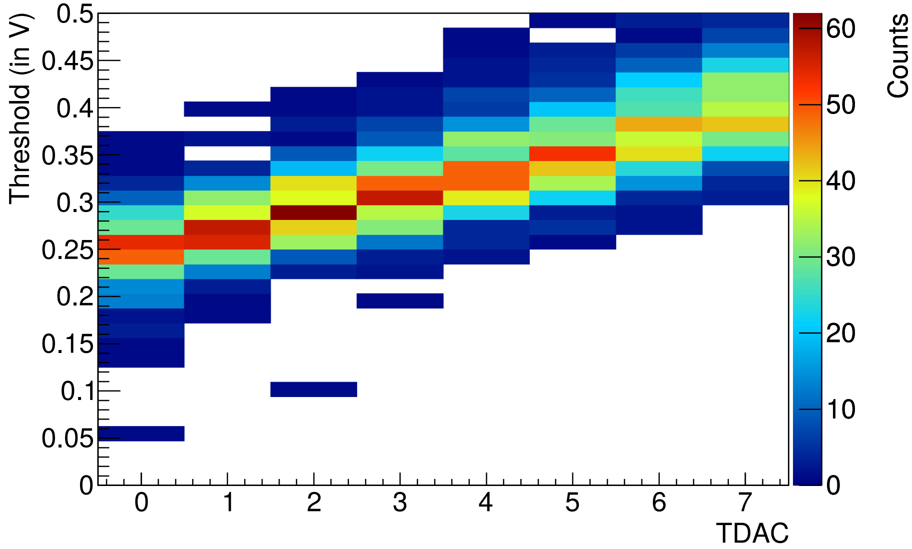
Karlsruhe Institute of Technology

- Charge injections of increasing strength are sent into a pixel
- Count number of detected signals → detection efficiency
- Shifted and scaled gaussian error function is fitted to the data points



Matrix Tuning

- The matrix implements a 3 bit tuning DAC and a disable bit for each pixel
- Writing of the pixel memories is working and the detection threshold changes linearly with the setting



Power Regulators – MinusReg