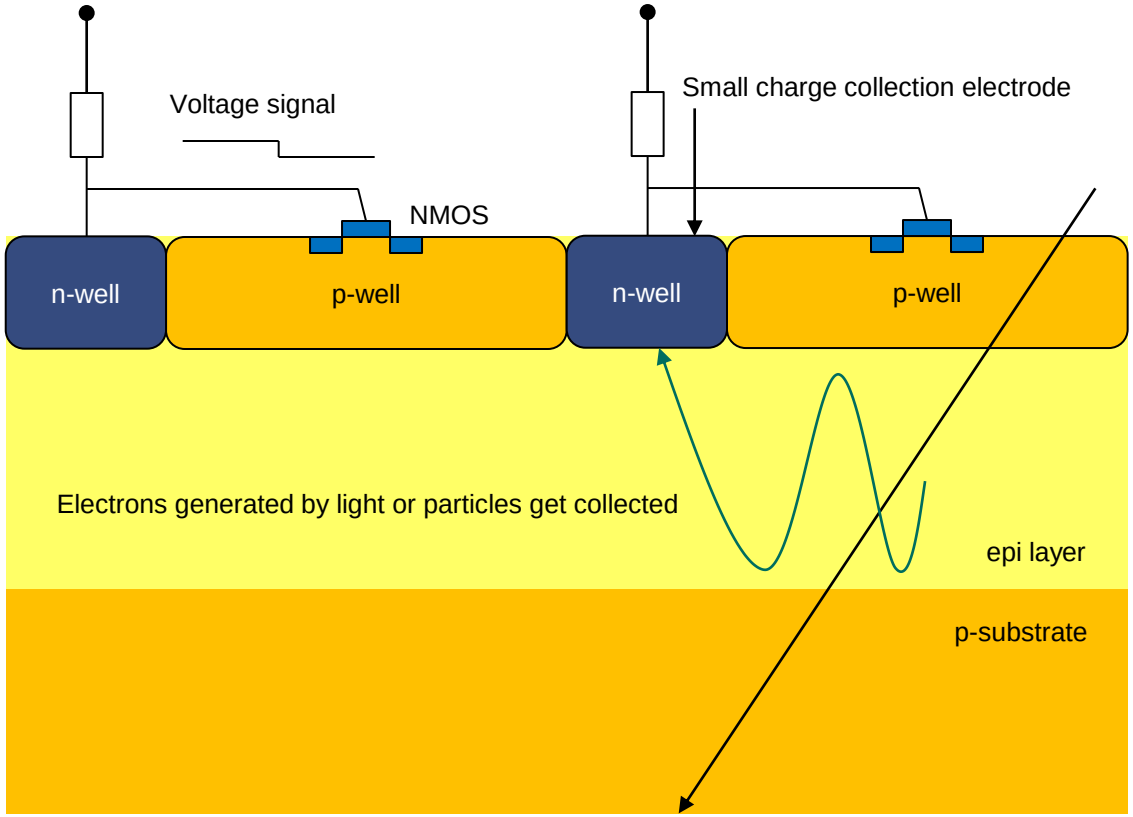
# HVCMOS Sensors

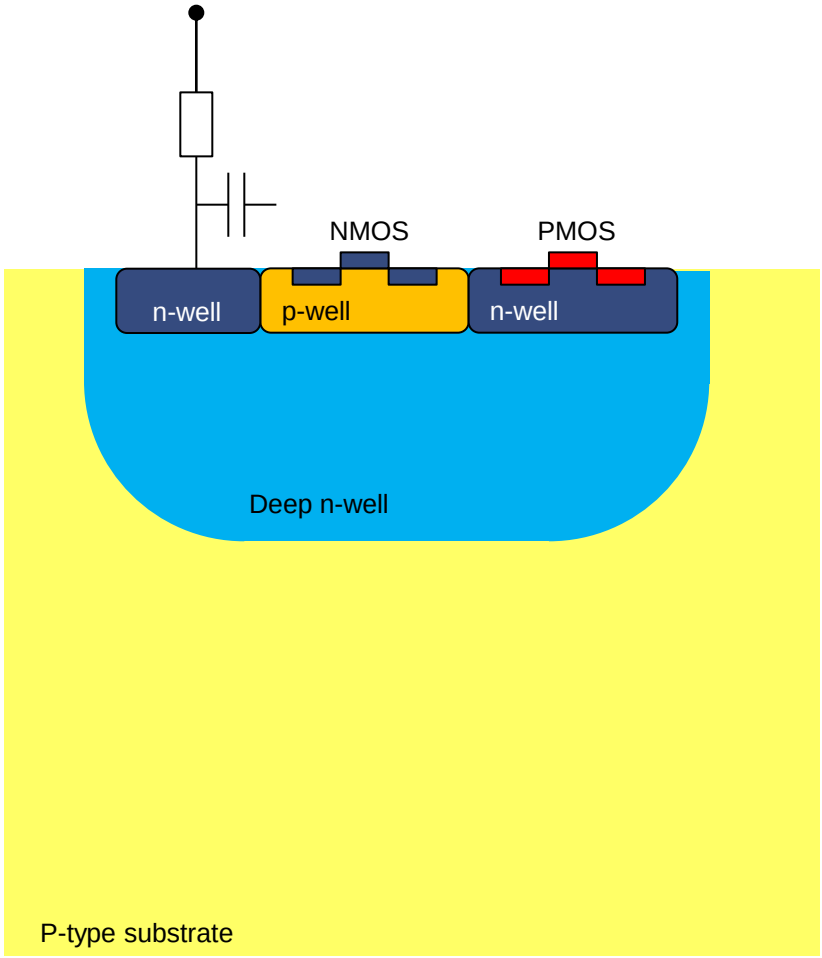
**Ivan Peric**

- HVCMOS Introduction
- Example sensor: Atlaspix3
- Technology improvements
- Applications
- Mu3e
- HIT beam monitor
- Compton telescope (AstroPix)
- Timing detector with 100ps resolution in SiGe technology of IHP
- CEPC
- Sensor for beam telescope
- PANDA micro-vertex detector
- MightyPix sensor for LHCb upgrade

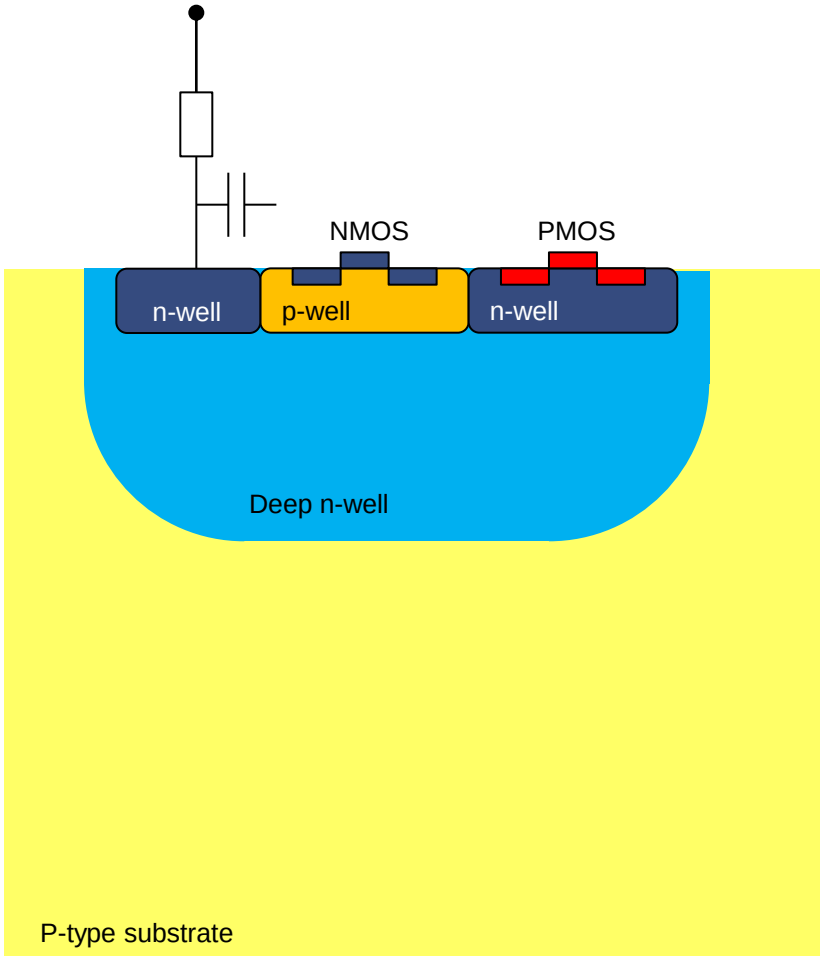
# INTRODUCTION


Voltage signal
Small charge collection electrode
NMOS
n-well
p-well
n-well
p-well
Electrons generated by light or particles get collected
epi layer
p-substrate

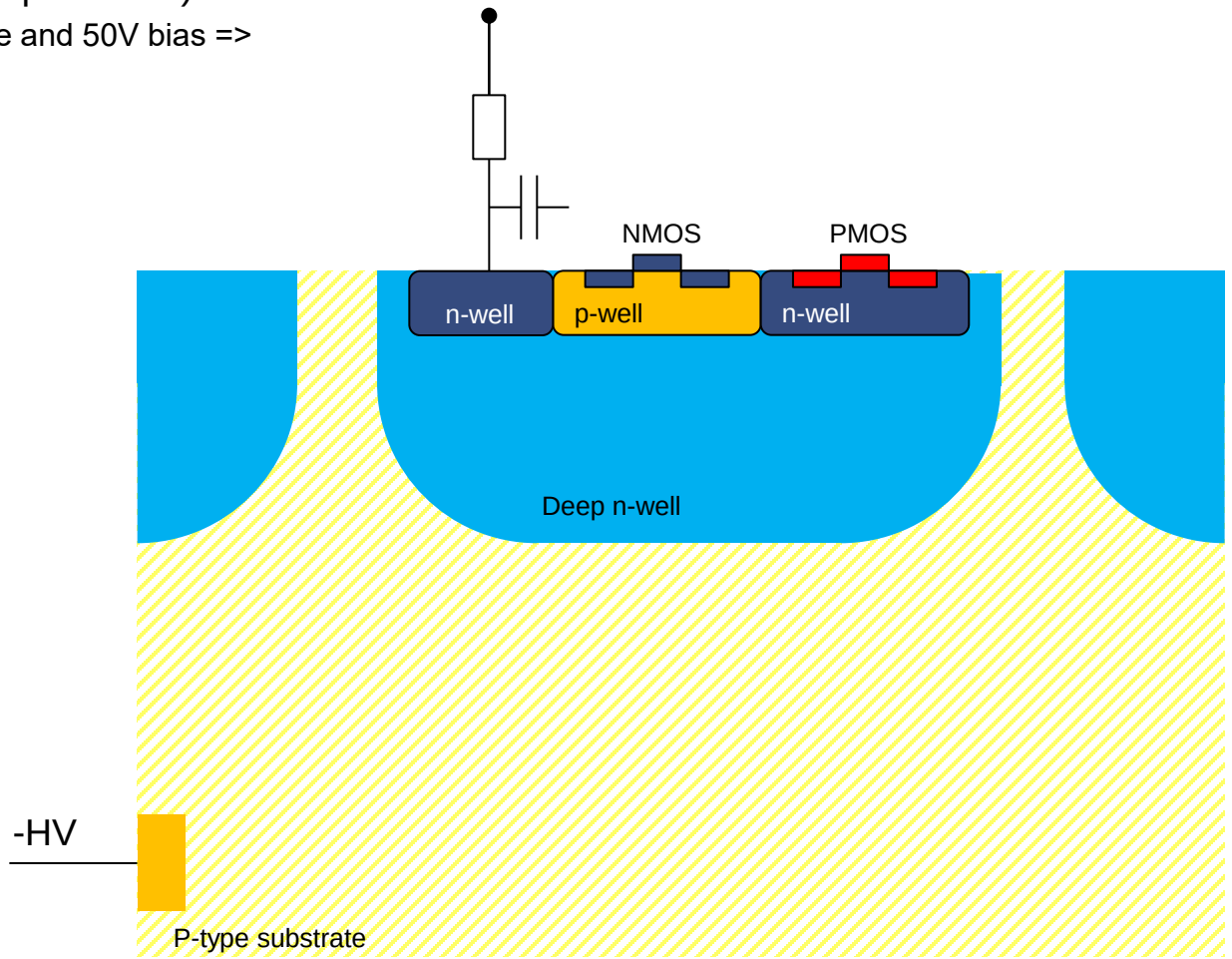
- Our Idea are HVCMOS pixel sensors
- Implemented in standard (HV)CMOS bulk process with triple well structure
- Pixels consist of large electrode with embedded readout electronics



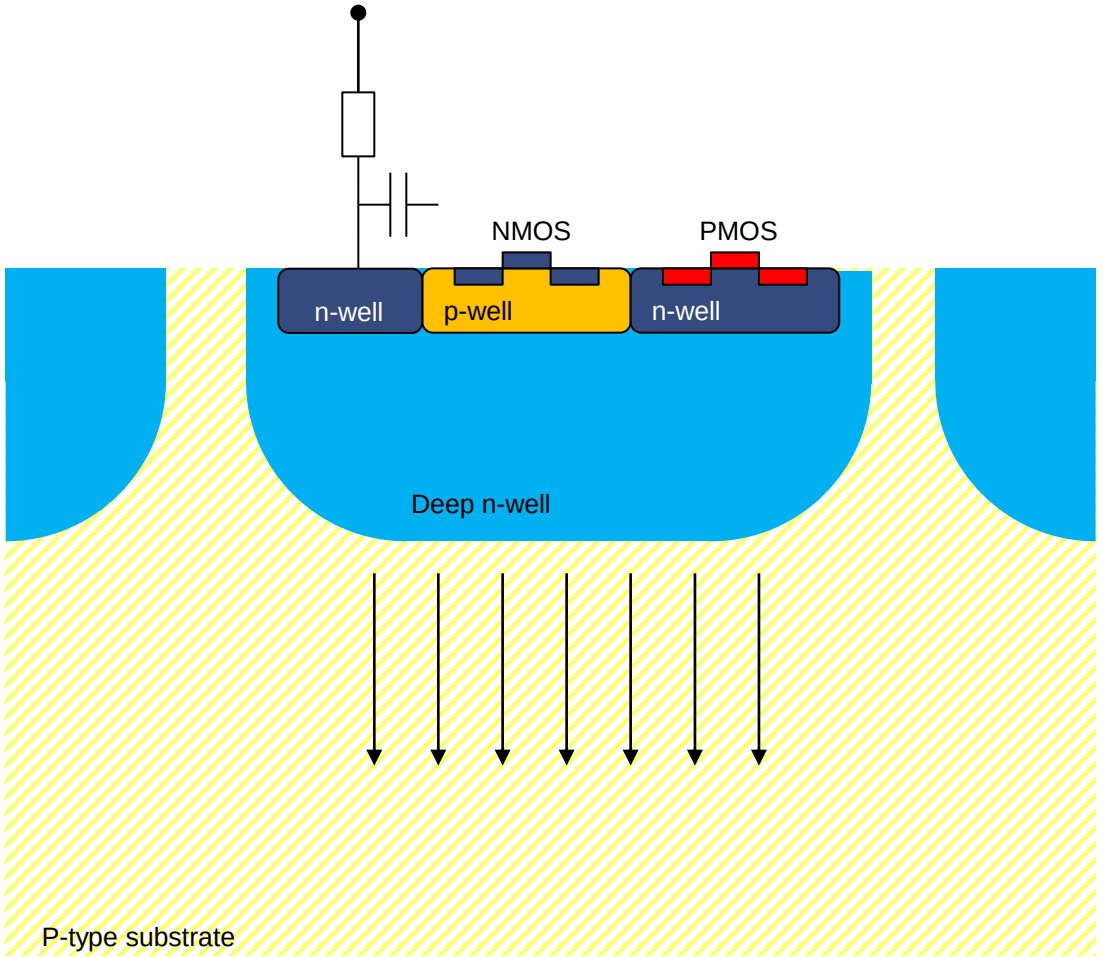
- The deep-n-well fulfils two tasks:
- 1. Local substrate for electronics (isolated from p-substrate)
- 2. Charge collecting electrode



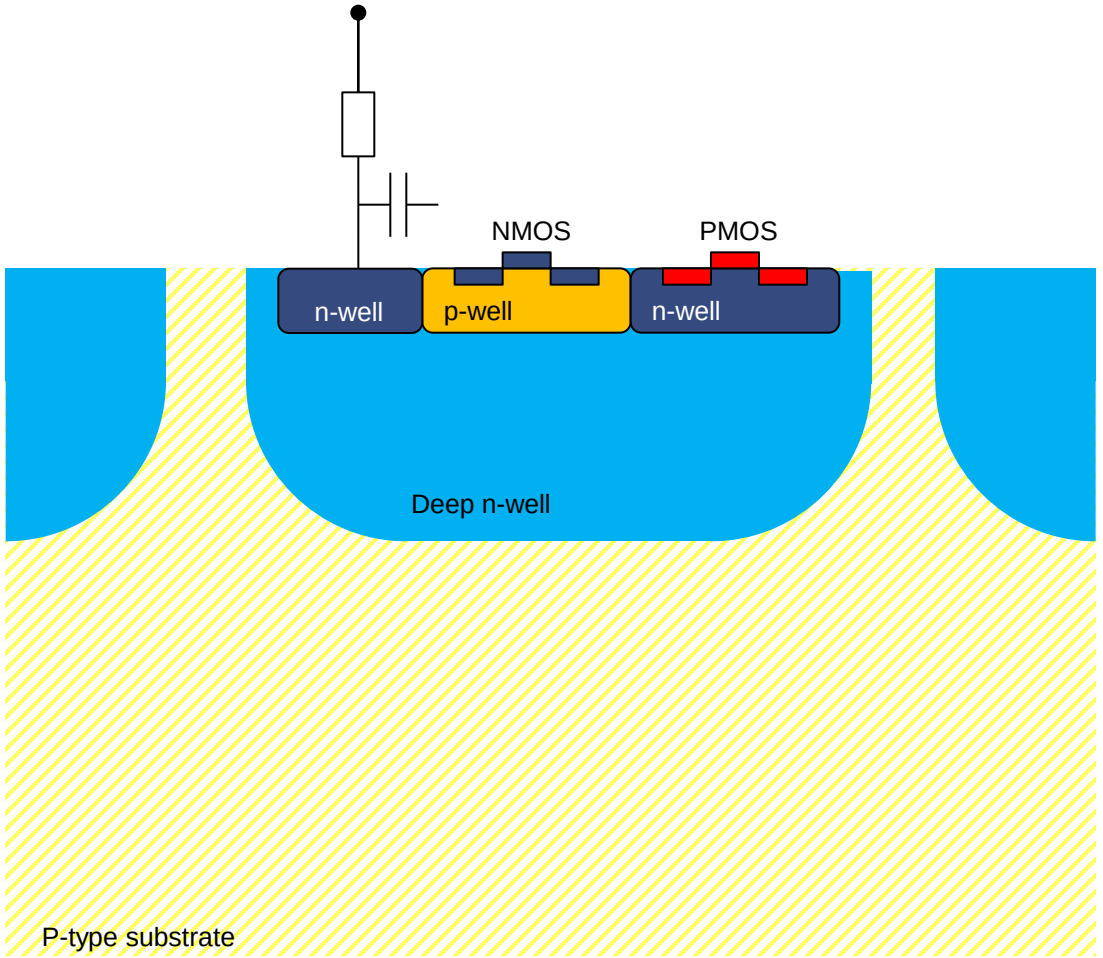
- Deep n-well isolates electronics from substrate
- Biasing of substrate with high voltage possible (typically |V| > 50V, up to 200V)
  - Example: 300Ωcm substrate and 50V bias => 30-50µm depletion
  - Larger depletion is possible



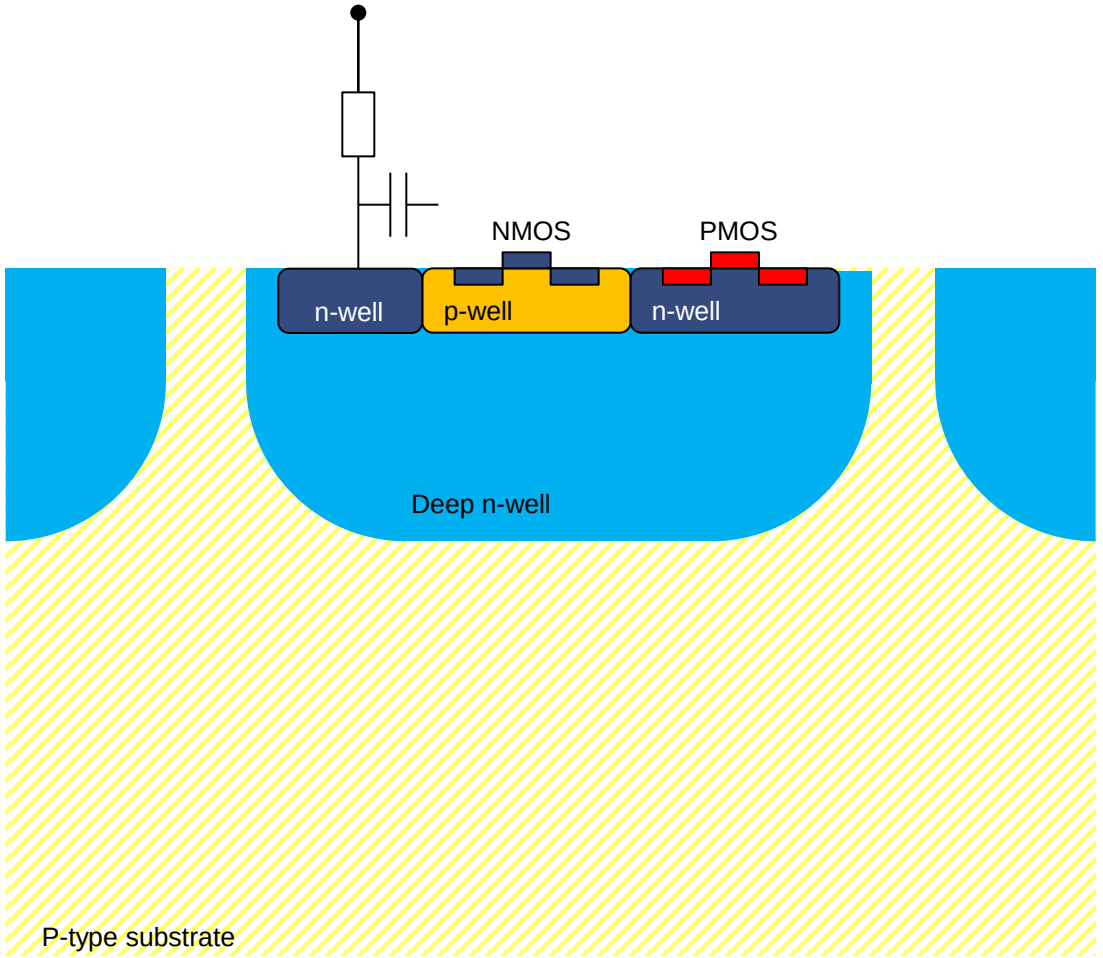
- Electron-hole pairs generated by particles are separated quickly in strong E-field.
- => Strong and fast signals when compared to standard MAPS



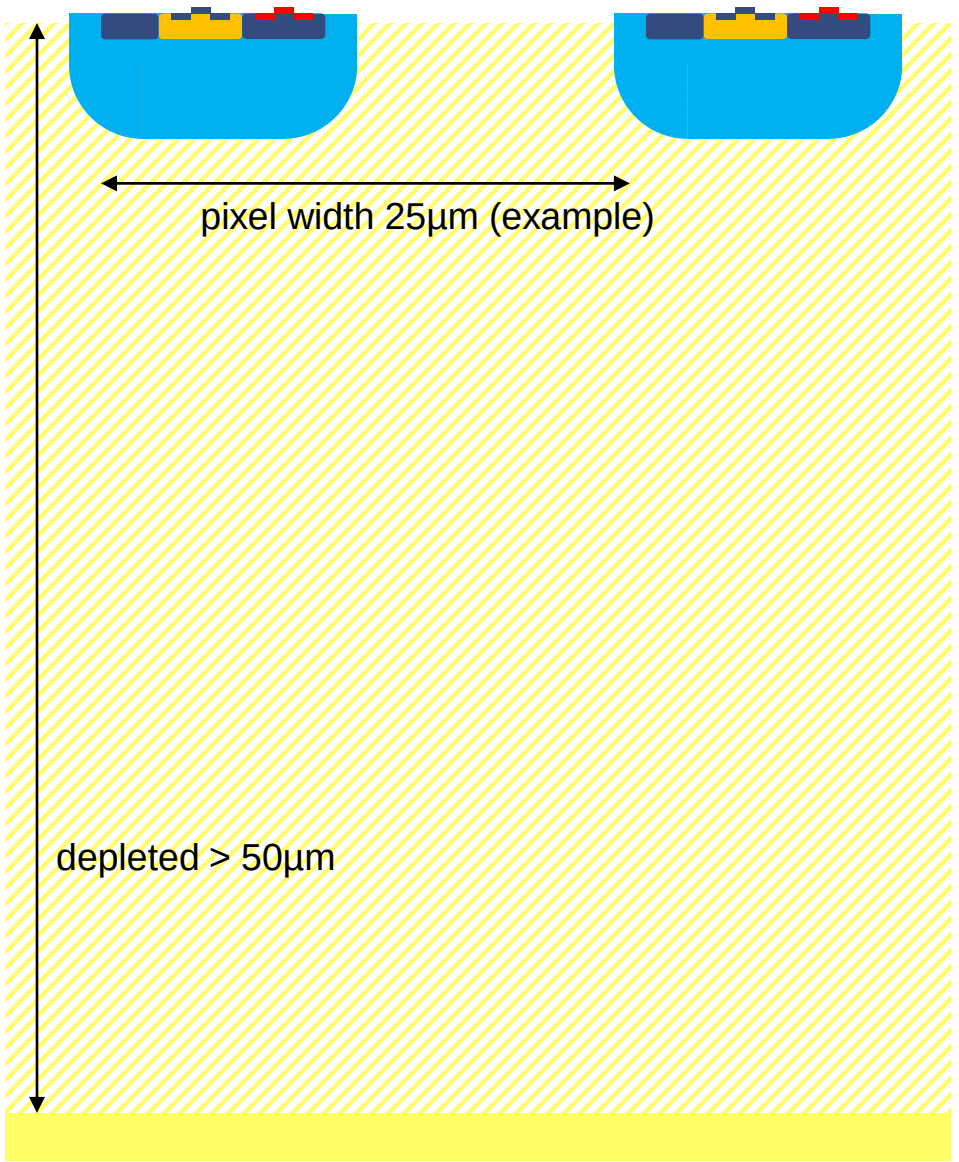
- HVCMOS sensors are compatible with many standard processes
- Implemented in several processes: UMC 65nm, AMS 350nm and 180nm, TSI 180nm, Globalfoundries 130nm, Lfoundry 150nm, IHP SG13S 130nm, HLMC 55nm
- Uniformly doped substrates with resistivity >=10Ωcm have been successfully used
- Since the bias voltage can be very high (some designs achieve ~200V), sensors work even with relatively low res substrates



- Radiation tolerant
- Can be implemented in standard IC-processes -> not expensive
- Can be thin
- Can have a high time resolution



- A bit larger capacitance but stronger signals vs MAPS

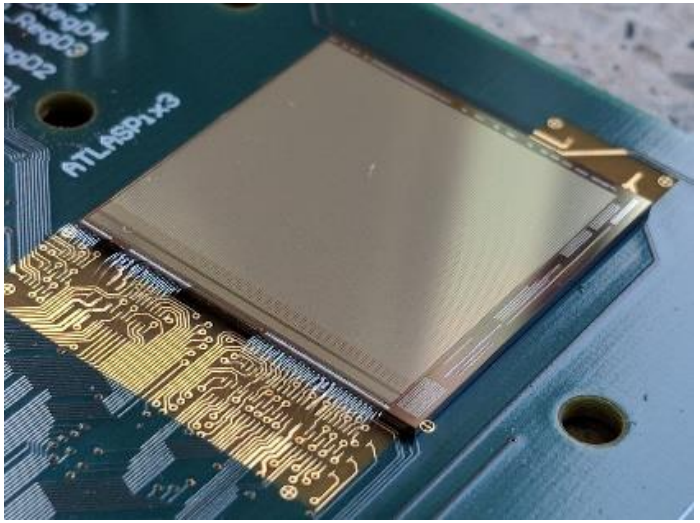


- R&D projects and applications
- The R&D has the aim to improve HVCMOS sensors for large area, high time, energy and space resolution
- Applications (HVCMOS)
- Mu3e
- HIT
- LHCb
- CLIC
- AMEGO-x
- CEPC
- PANDA
- DESY beam telescope
- and others

EXAMPLE

- Example of HVCMOS sensor AtlasPix3 (Tests started in 2019)
- AtlasPix3 sensor was originally developed for ATLAS, it is now used as technology demonstrator for HVCMOS. First HVCMOS sensor in reticle size implemented in 180nm HVCMOS process of TSI. High resistivity substrates of 300Ωcm
- Pixels of 50µm x 150µm
- Chip size 2.2 cm x 2.0 cm, matrix size 19.8 mm x 18.6 (132 x 372)
- Pixels contain amplifiers and comparator with threshold tune circuit, comparator is NMOS only
- Triggered and untriggered (continuous) readout
- Serial powering
- Clock data recovery from command in
- Power consumption 140mW/cm$^2$

| Chip area/thickness | 2 cm × 2 cm / 250 µm |
|---|---|
| Pixel size | 50 µm × 150 µm |
| Detection efficiency | 99% in 25 ns time window |
| Noise rate per pixel | 5 Hz – 40 Hz/pixel |
| Power consumption | <500 mW/cm$^2$ (preferably 150 mW/cm$^2$) |
| Current consumption | <240 mA/cm$^2$ |
| Radiation doses | 800 kGy TID & 1.5 $10^{15}$ $n_{eq}$/cm$^2$ NIEL |
| Operating temperature | - 25 °C (maximum ratings - 55 °C to +60 °C) |
| Signal, Noise and threshold | S > 2.06 Th for 99% of signals and pixels |



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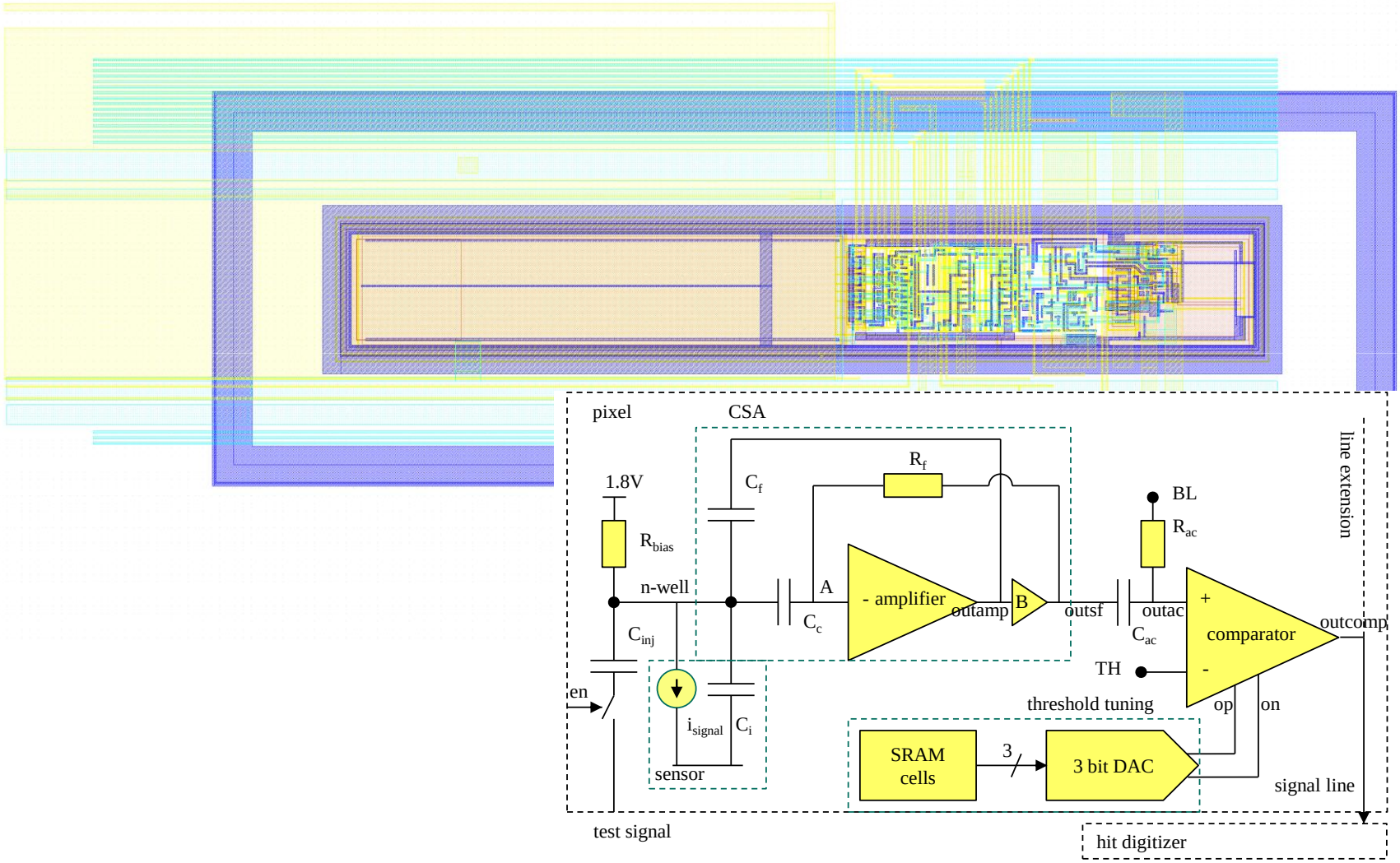

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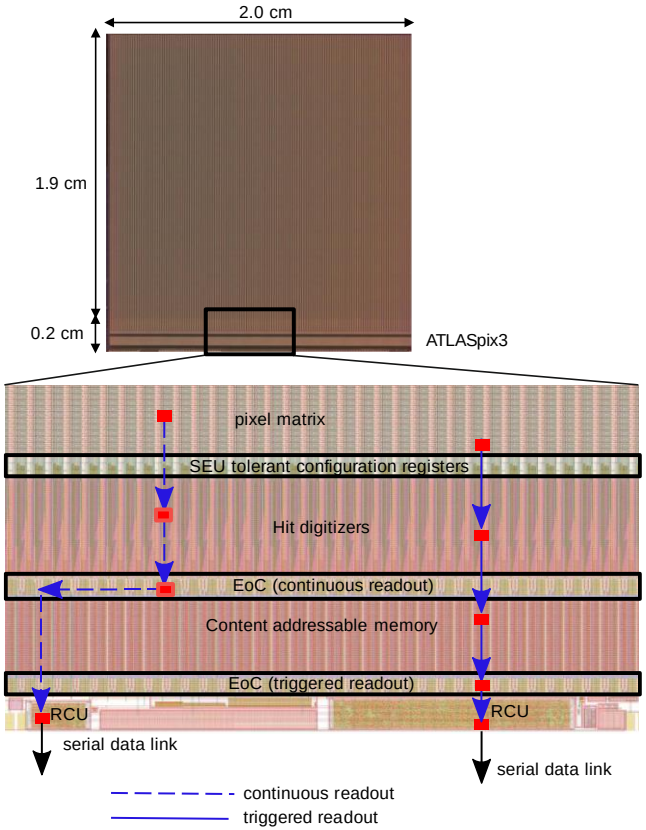
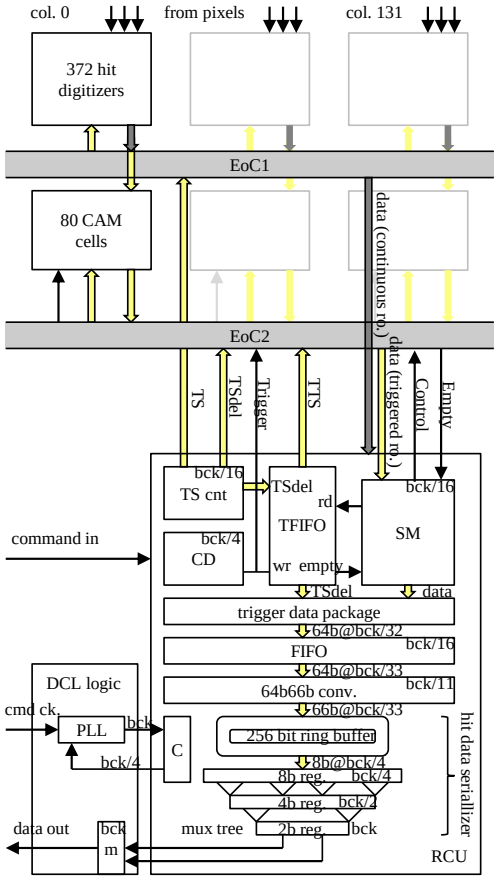
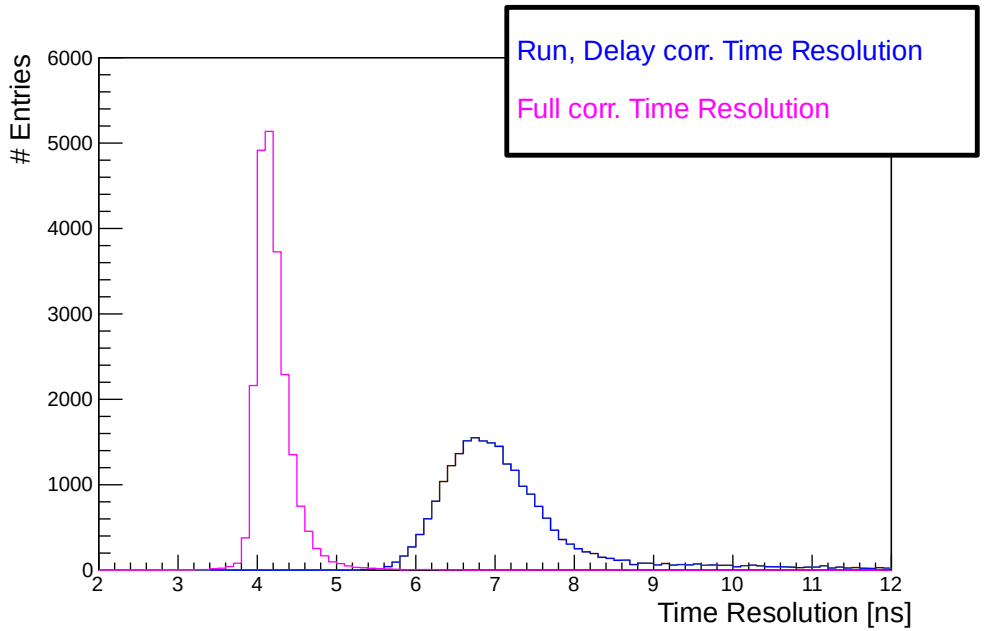


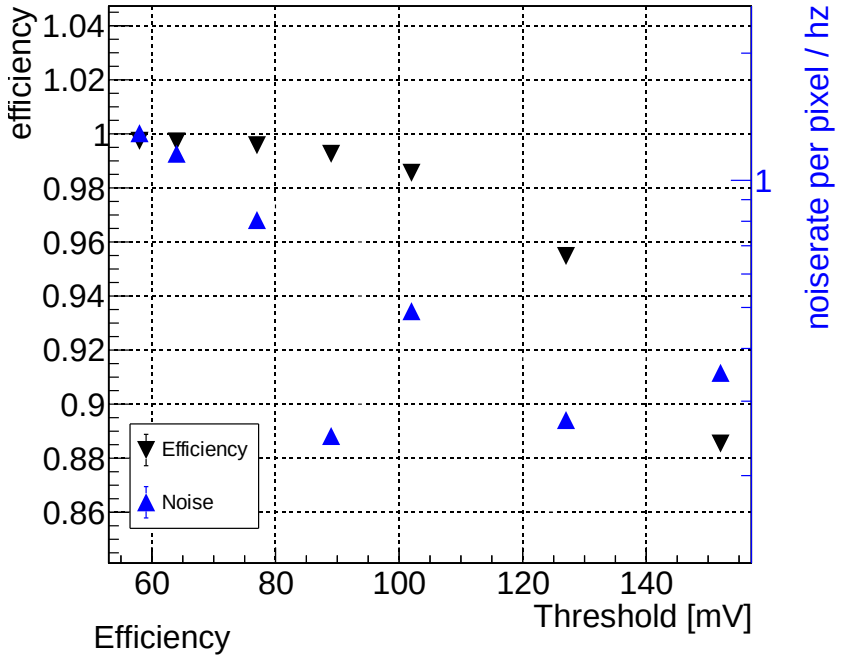




I. Peric et al, High-Voltage CMOS Active Pixel Sensor, IEEE Journal of Solid-State Circuits (Volume: 56, Issue: 8, Aug. 2021) https://doi.org/10.1109/JSSC.2021.3061760

- Time resolution and efficiency measured in PSI test beam (Dohun Kim and Heidelberg team)

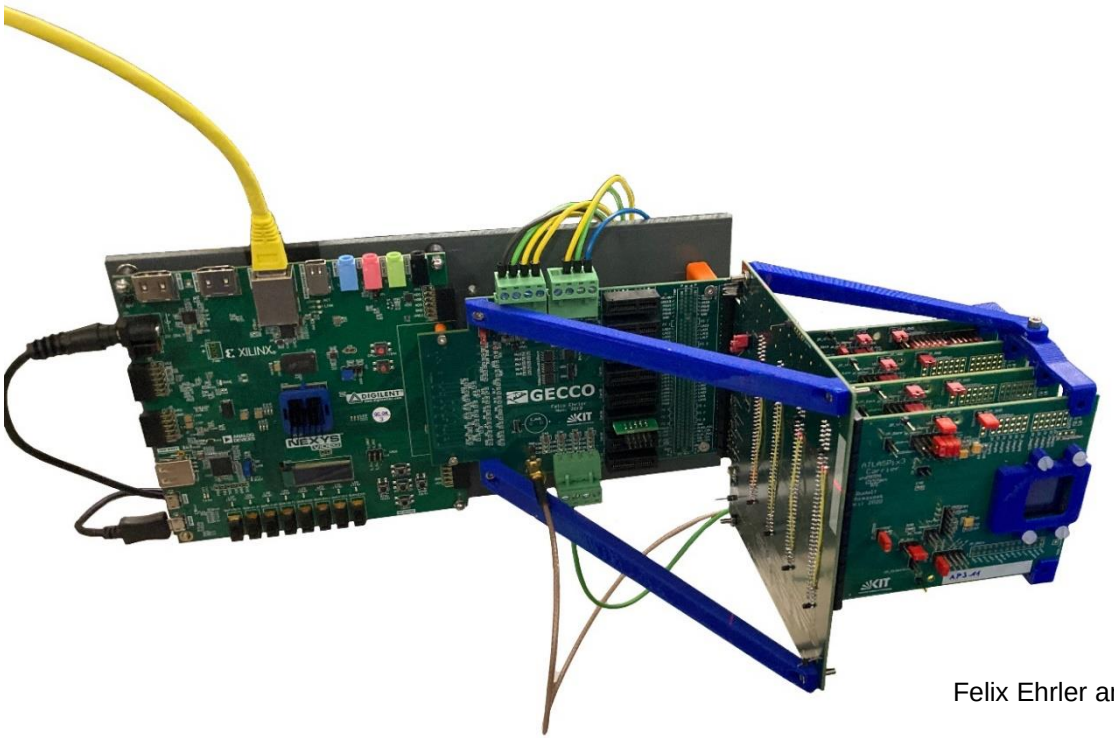



Time resolution (RMS) for every pixel
Uncorrected 6.7ns +- 0.5ns
ToT corrected 4.1ns +- 0.1



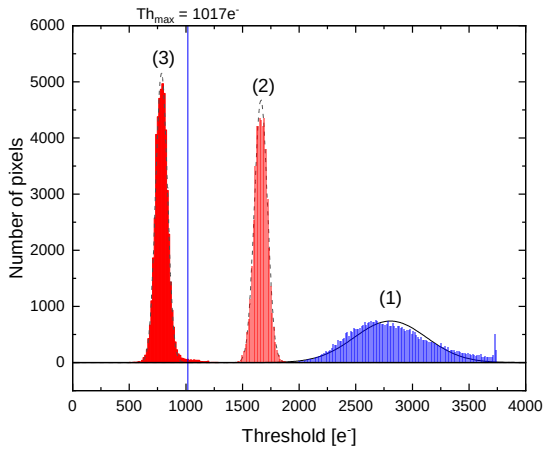

Efficiency

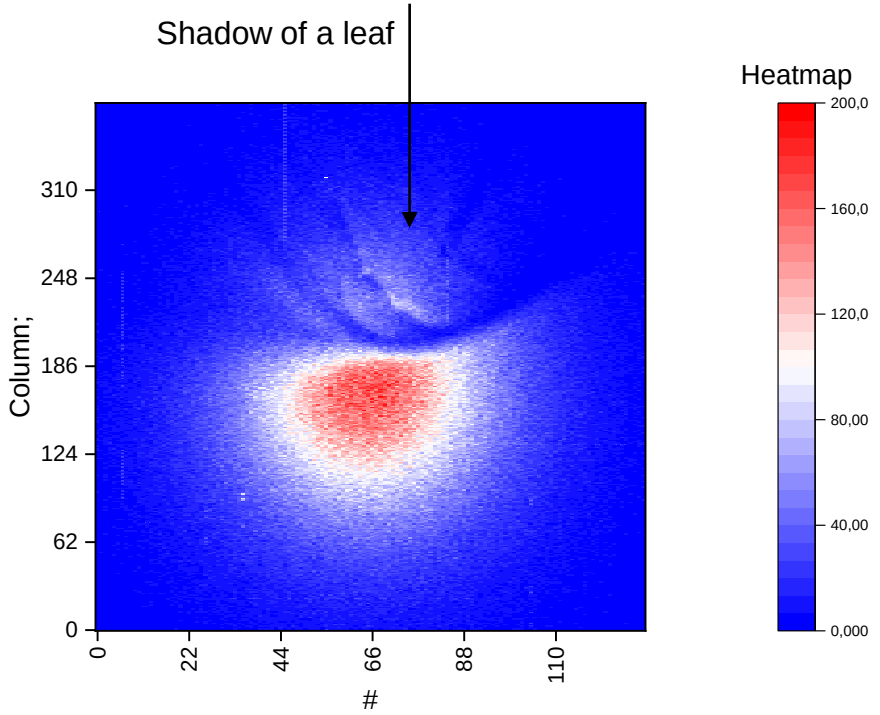
- For AtlasPix and other sensors, have developed a modular test system called Gecco that is based of several PCBs, commercial FPGA board and self-made software a firmware. The test system can be used for single chip tests and as beam telescope



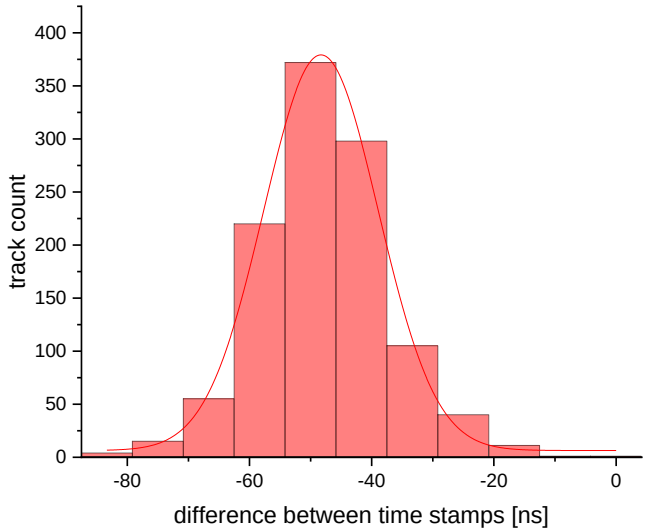

Felix Ehrler and Rudolf Schimassek

- Some results at KIT
- Threshold can be tuned to 800e, threshold dispersion 60e, noise around 70e
- Example: $^{55}$Fe source measurement

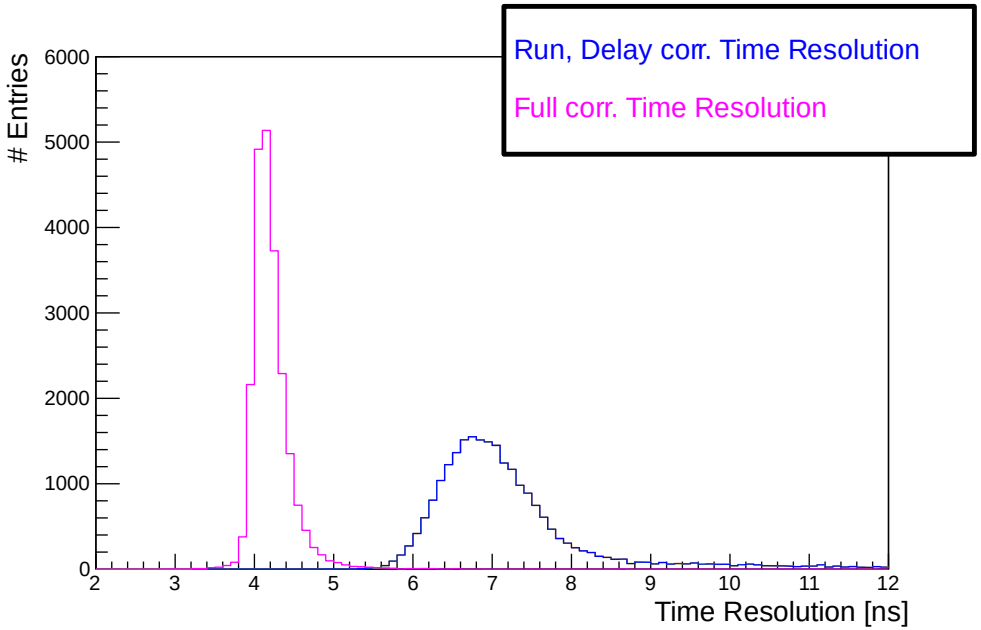


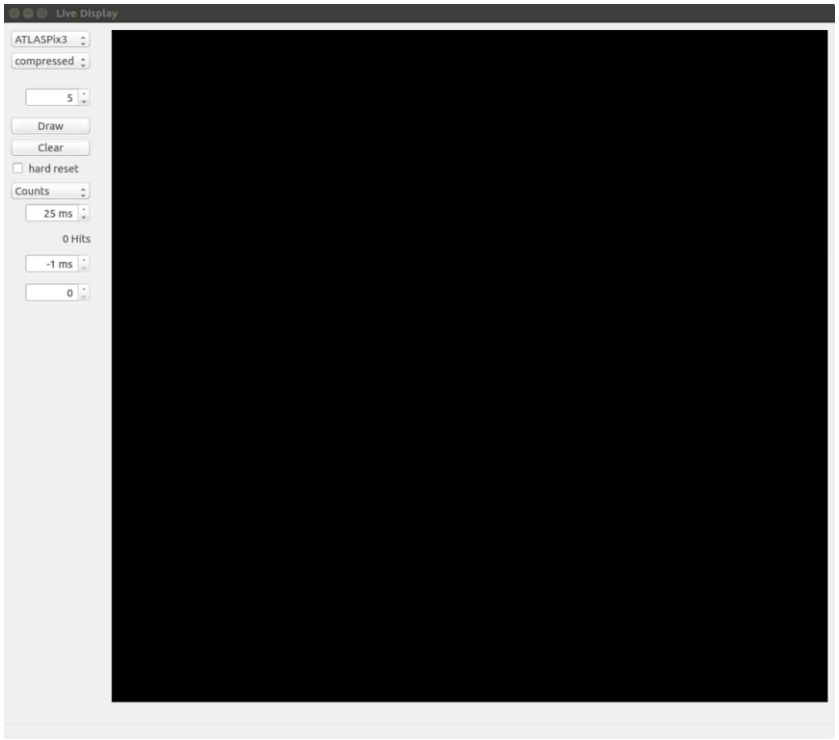
- Thanks to large sensor area, simple tests of time resolution and efficiency can be performed with cosmic particles. Results are comparable to those obtained by test beam



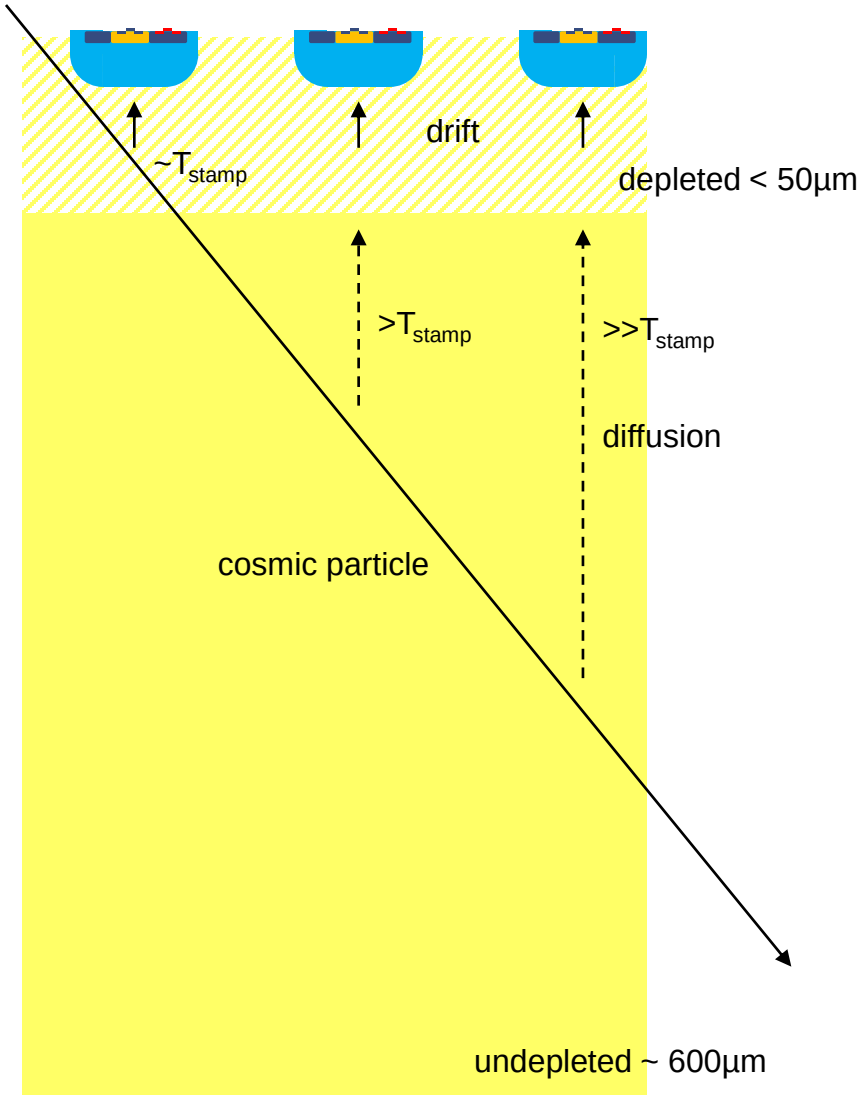

Cosmic particles: Uncorrected time resolution 6.6ns (first hit)




Test beam: Time resolution (RMS) for every pixel
Uncorrected 6.7ns +- 0.5ns



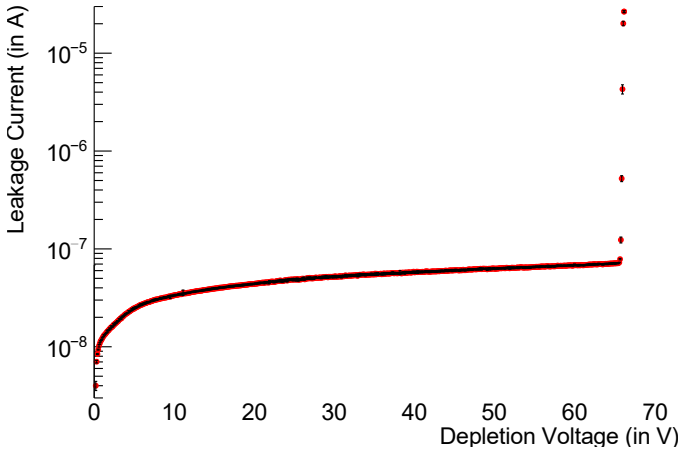

Slow motion of charge collection with time resolution of $T_{stamp}$ = 8.3ns

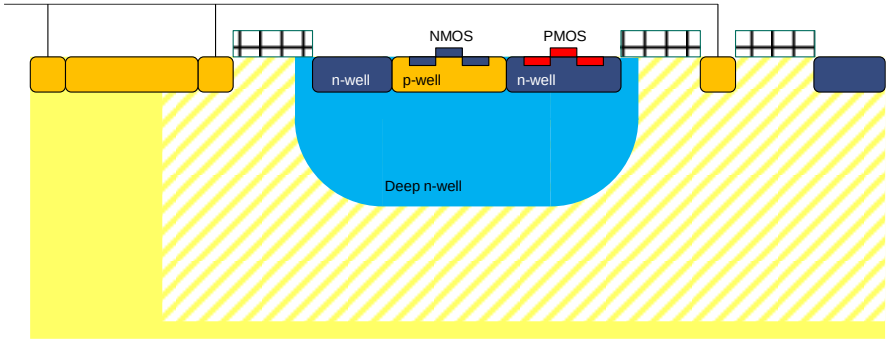


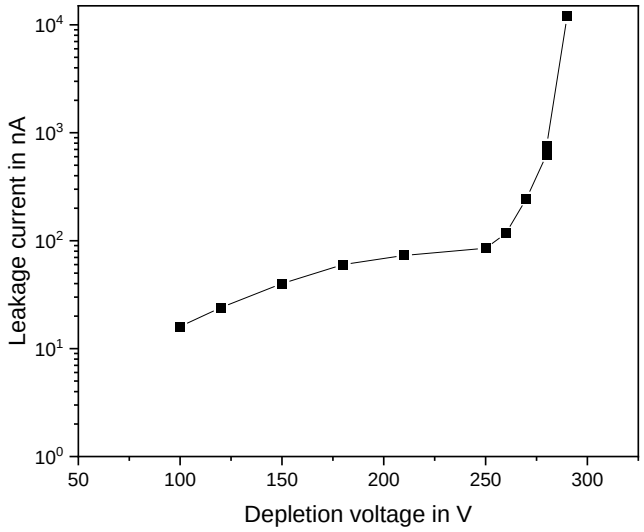
# SENSOR TECHNOLOGY DEVELOPMENTS IN PAST 2 YEARS

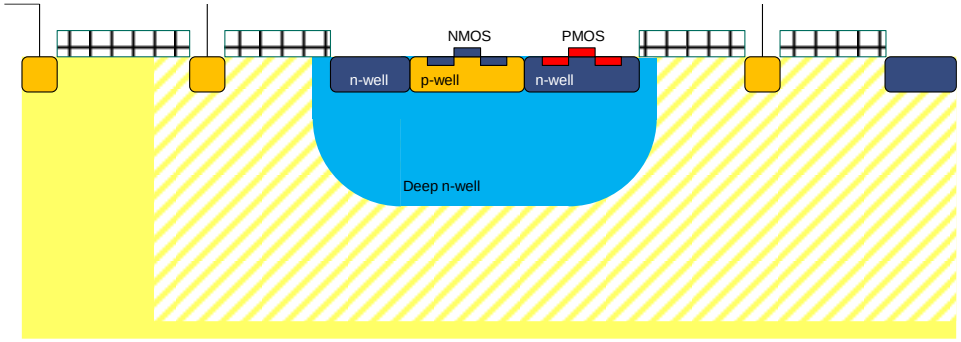
- Although working well, ATLASpix has some limitations
- Too early breakdown
- Comparator nonideal design (NMOS-based or on periphery)
- Large pixel size
- Time resolution and energy resolution can be improved

- We improved breakdown from ~65V to > 200V

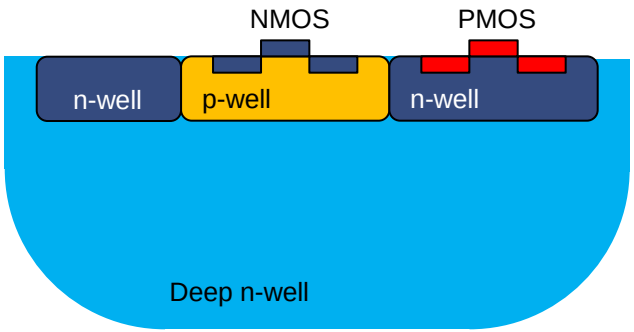


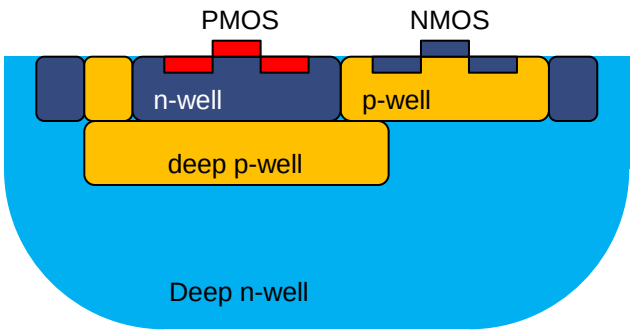



- Additional layer deep-p-well to isolate n-well from DN
- Allows more flexibility in design

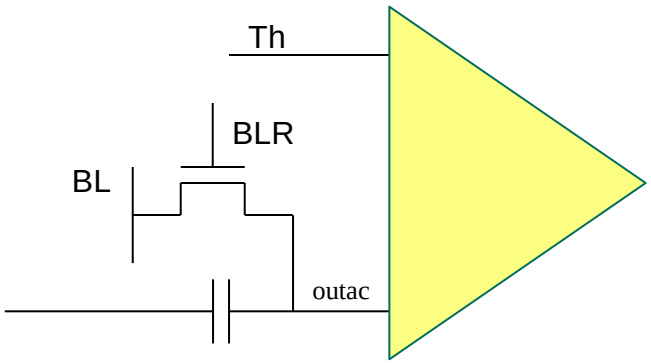


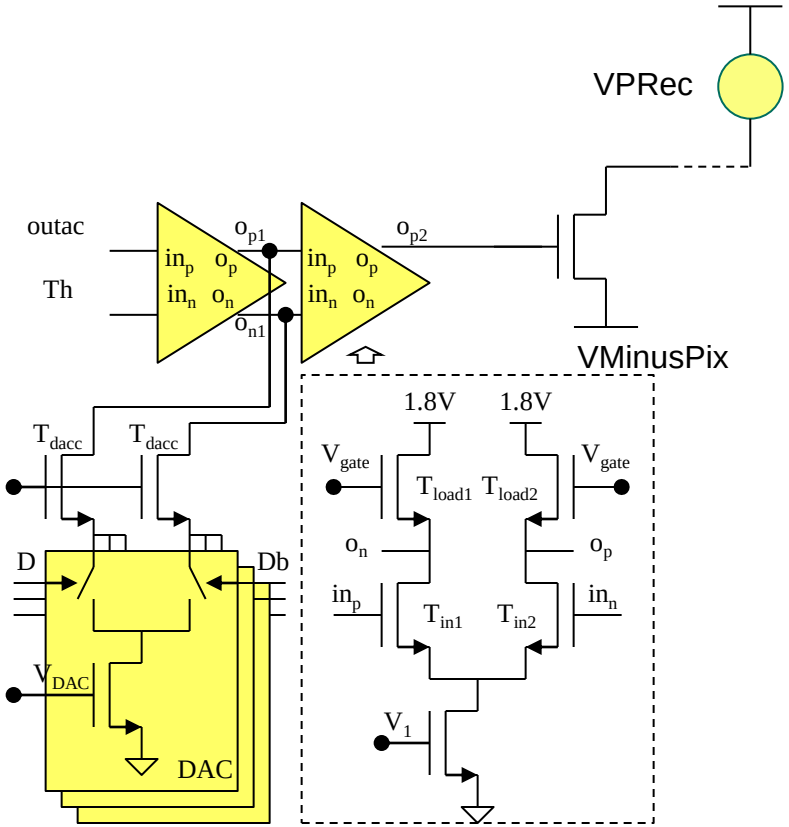

Without deep p-well



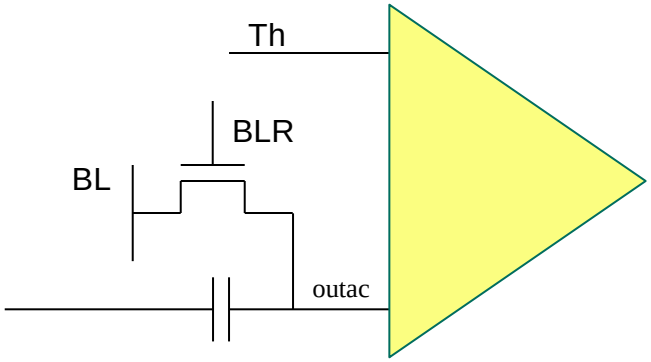

With deep p-well

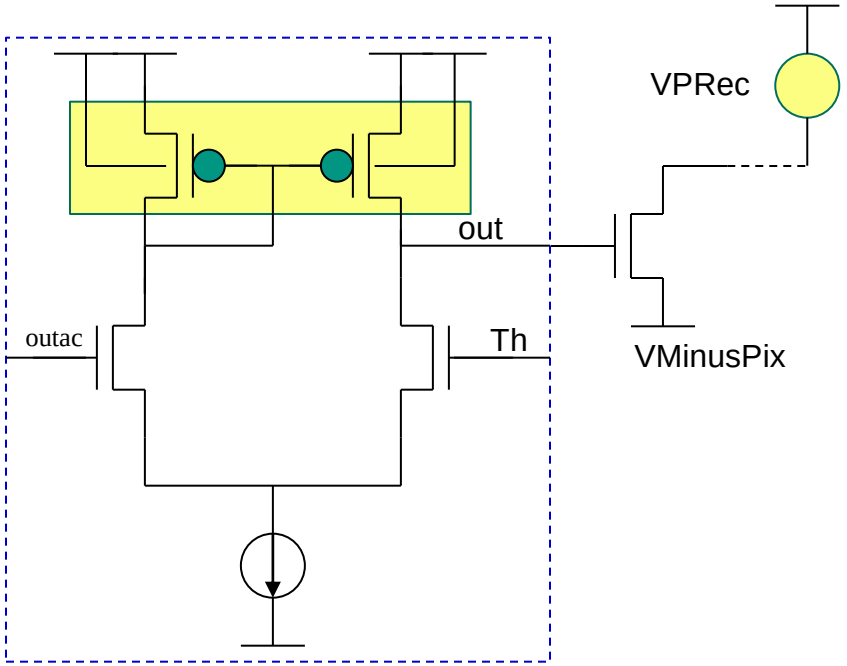
- NMOS comparator
- Drawback, requires DC bias current > 1µA

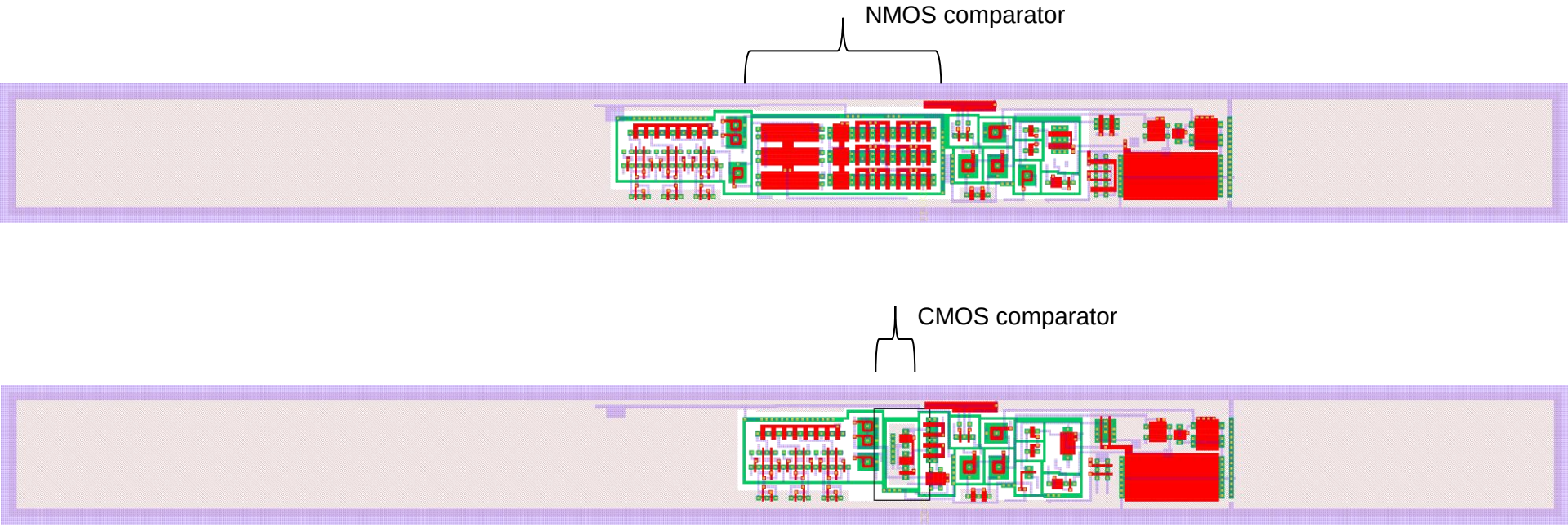


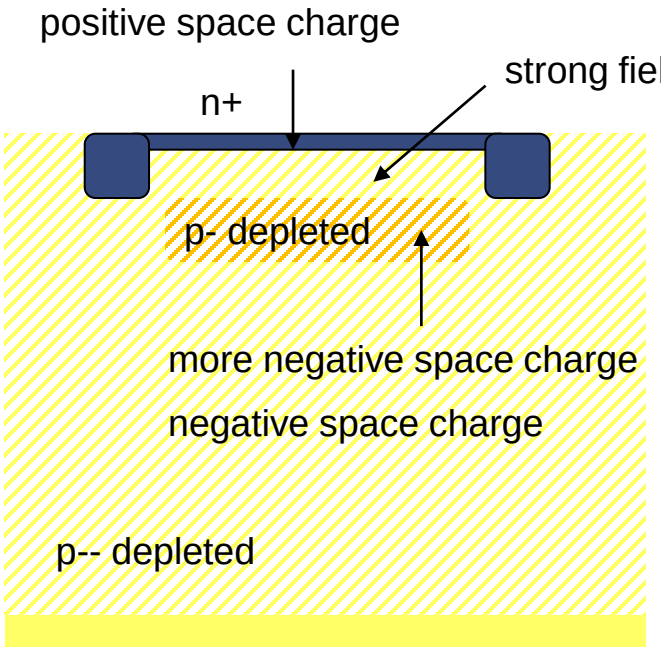
- With the deep p-well we can use CMOS comparator
- Works with smaller bias current

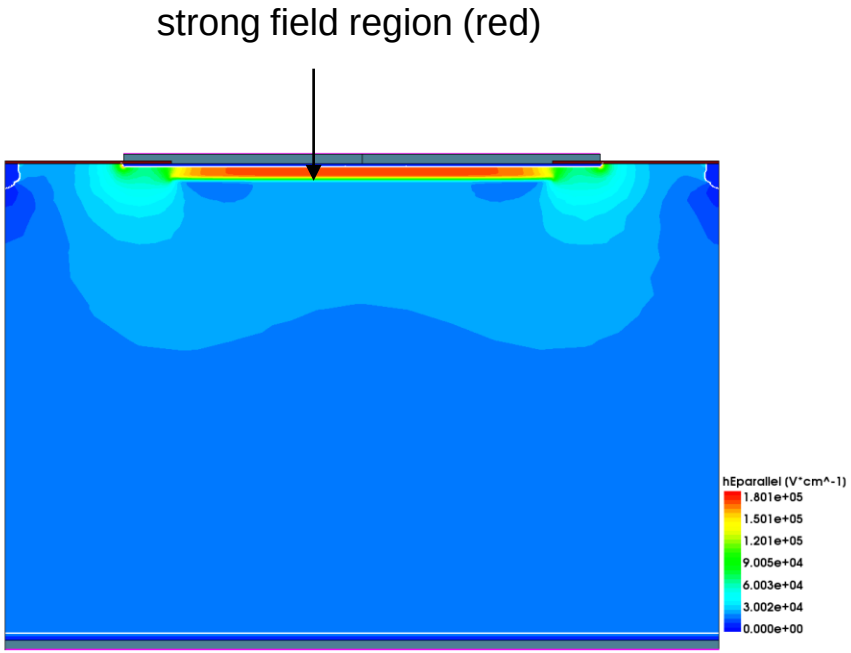



NMOS comparator
CMOS comparator

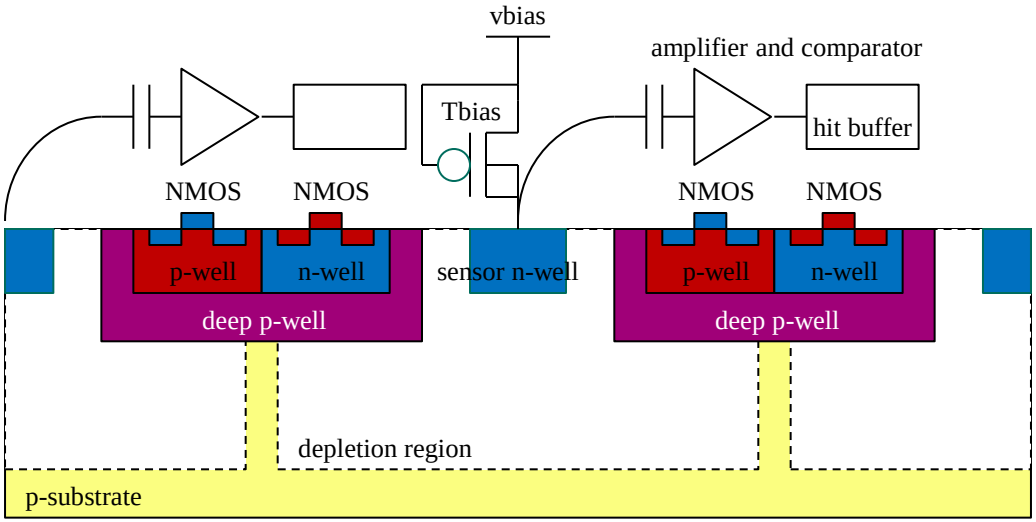
- Similar implant (same energy, smaller dose) can be used to implement LGADs




Design & Simulations - Ekaterina Trifonova (KIT)

- H25: A test matrix with DMAPS-like pixels (low fill factor) that use deep p-well. The pixel size is 35µm x 25µm



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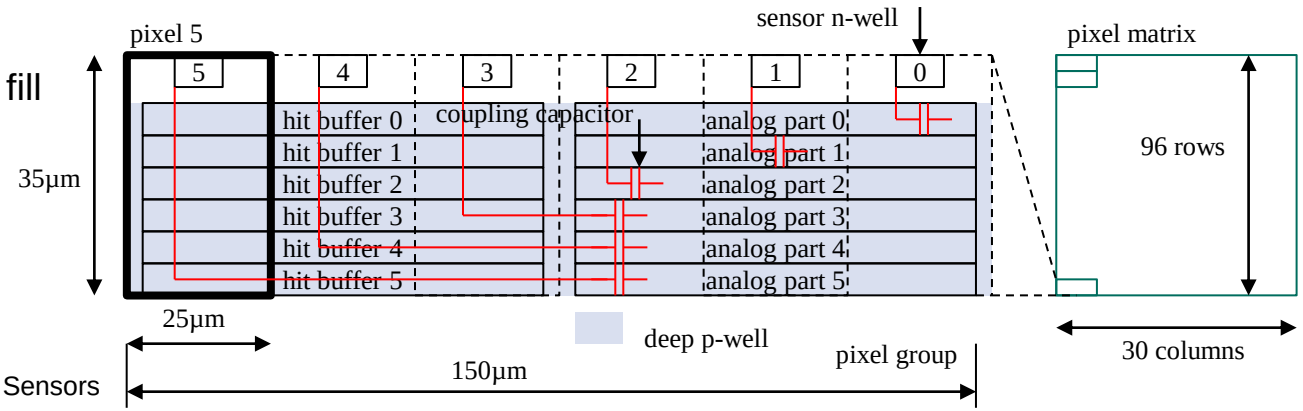
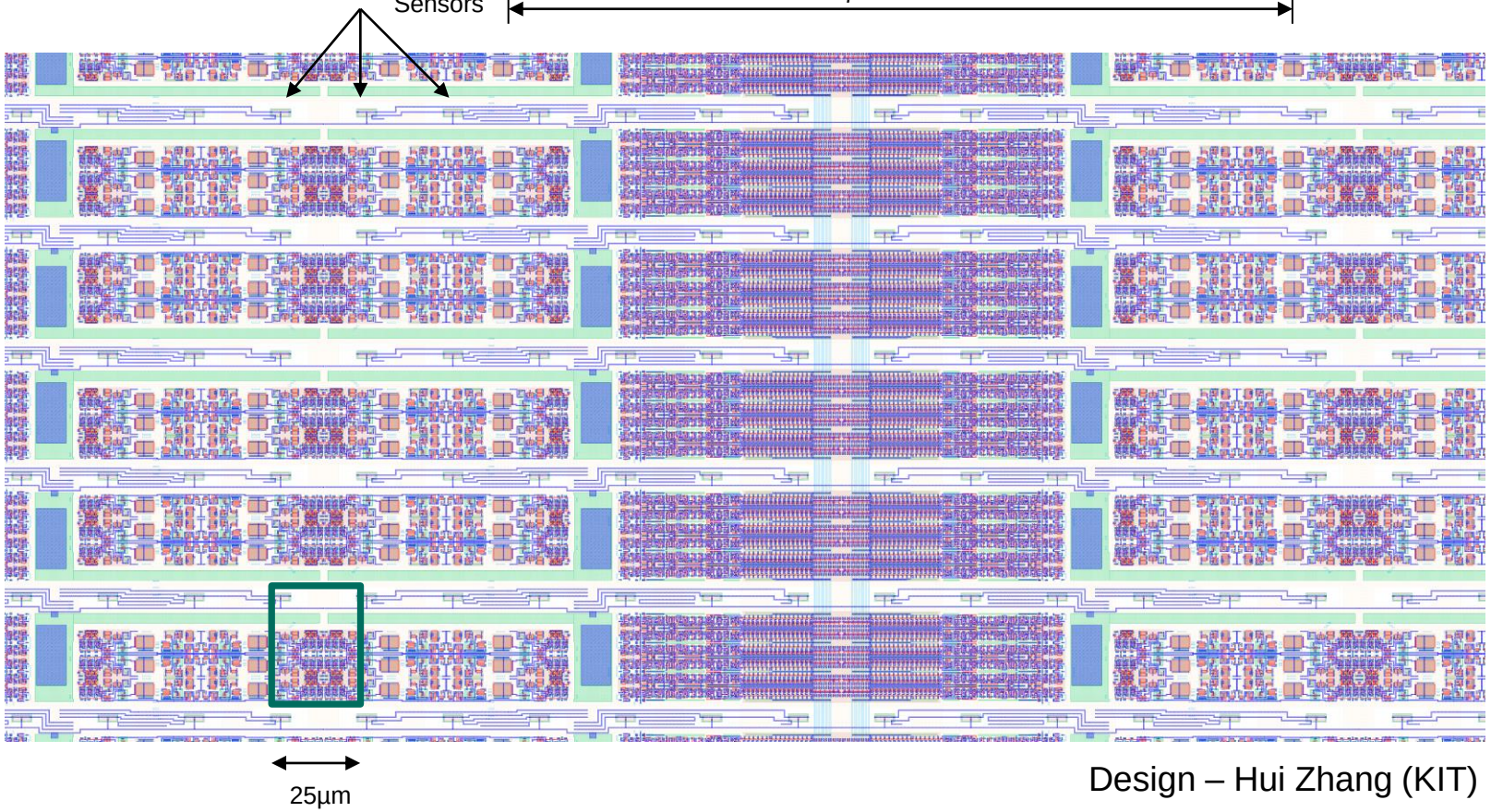
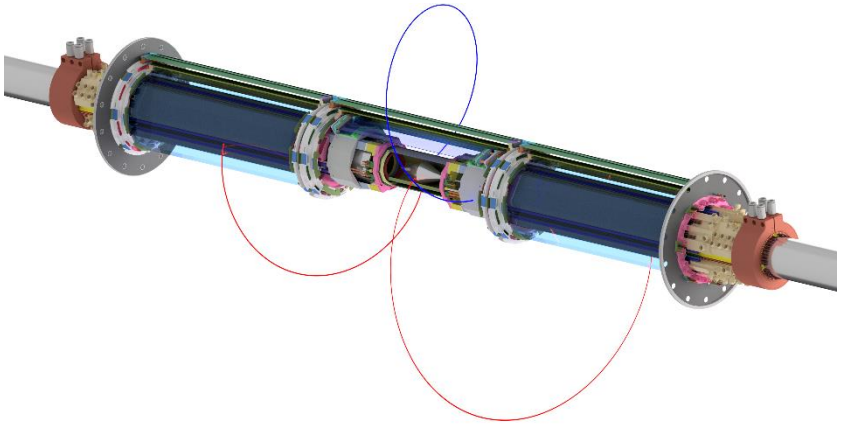


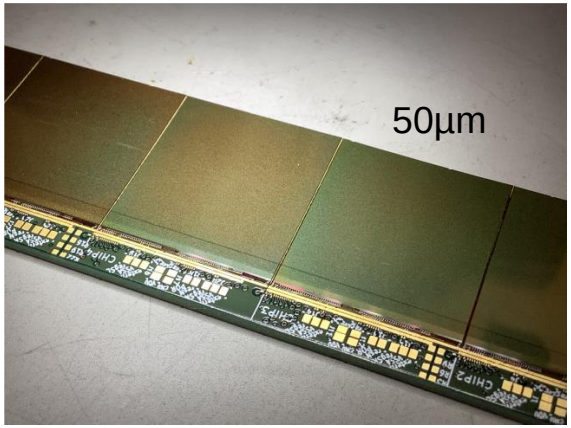




Design – Hui Zhang (KIT)

# SELECTED APPLICATIONS IN EXPERIMENTS AND DETECTORS

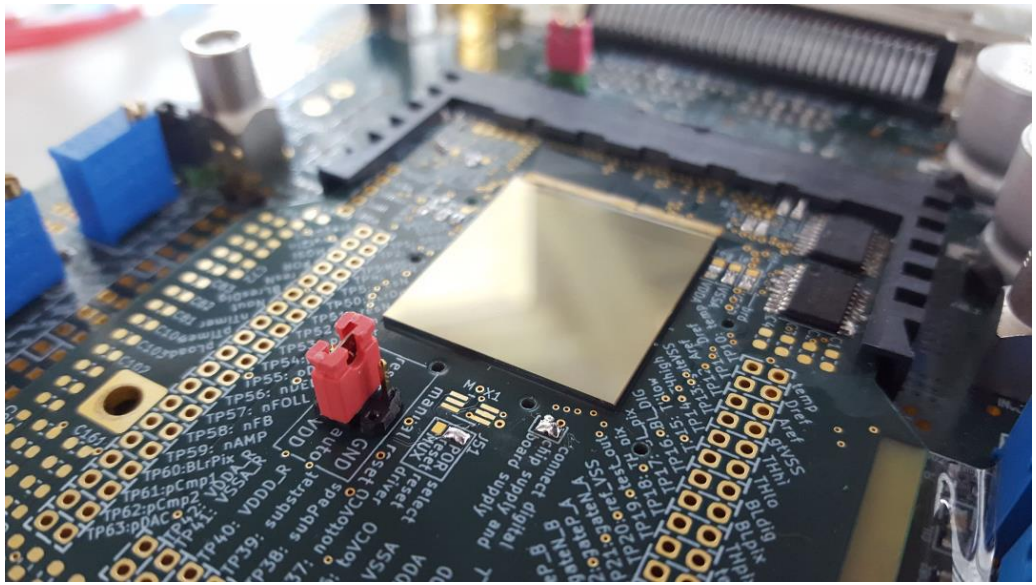
- Mu3e is an experiment at PSI/Switzerland with the goal to search for lepton flavour violating decay
- Conservation of lepton number is accidental symmetry -> Great chance for important discovery
- Mu3e pixel detector will contain 4 pixel-layers with a total sensor area of more than 1.1m2
- 2844 sensor chips called MuPix (sensor area 4cm$^2$ + periphery) tinned to 50µm will be glued to Al printed flex and connected by SPTAB. Flex foils will serve as support structure






Mu3e ladder

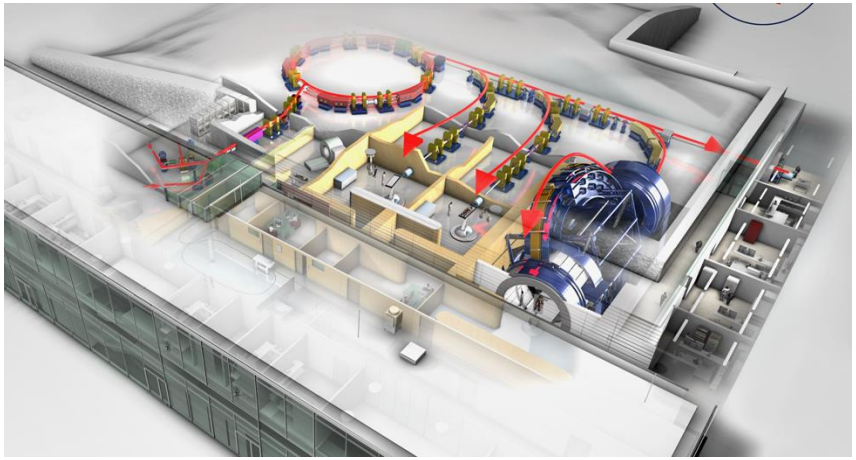
- MuPix is a reticle size sensor produced in TSI 180nm HVCMOS process on 300Ωcm substrates.
  - 256 x 250 pixels of 80 x 80µm$^2$ size. The chip area is 20.66mm x 23.18mm.
  - Pixels contain charge sensitive amplifiers – no comparator
  - Connected to hit digitizers
  - Hit digitizers contain comparators and digital circuits
  - 4 data links (4 x 1.28GBit/s), possible to process 120MHits/s
- The construction of the detector is planned for 2023

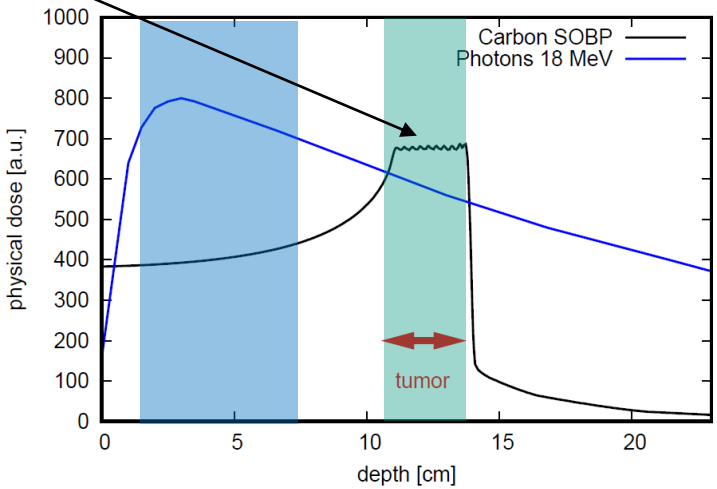


A photograph of MuPix10 mounted on a test-board

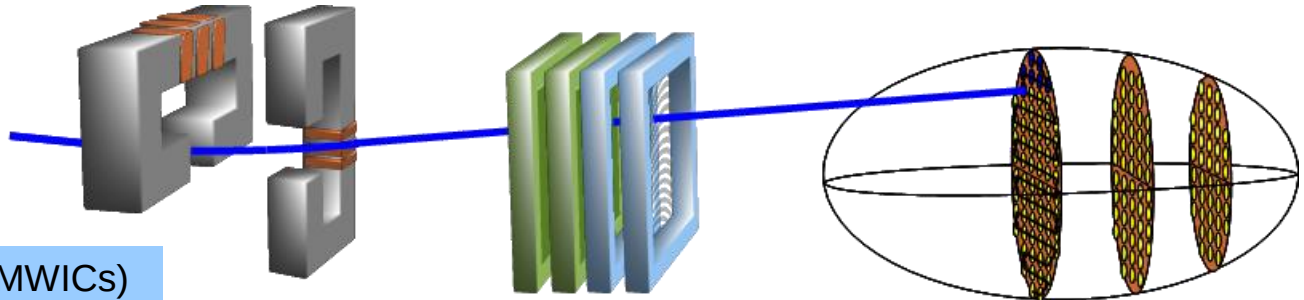
- Pixel sensor requirements
- Sensor dimensions [mm$^2$] ≤ 21 × 23 (active 20 × 20)
- Thickness [µm] ≤ 50
- Spatial resolution µm ≤ 30
- Time resolution [ns] ≤ 20
- Hit efficiency [%] ≥ 99
- Number of LVDS links (inner layers) 1 (3)
- Bandwidth per link [Gbit/s] ≥ 1.25
- Power density of sensors [mW/cm$^2$] ≤ 350
- Operation temperature range [°C] 0 to 70

- Heidelberg ion beam therapy facility (HIT)
- At HIT, tumors are treated using proton and carbon ion beams
- For each energy slice the ions can be scanned over the target volume
- Less radiation dose outside the target volume

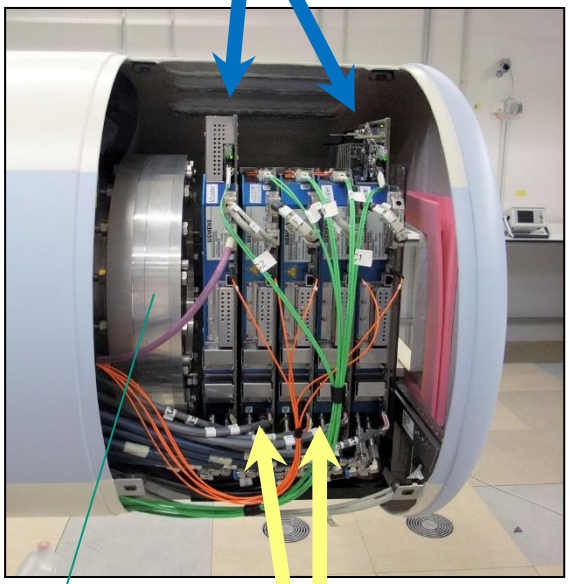




- HIT aims MRT-compatible replacement/upgrade of the existing beam monitor



Multiwire chambers (MWICs) for position measurement



beam exit window

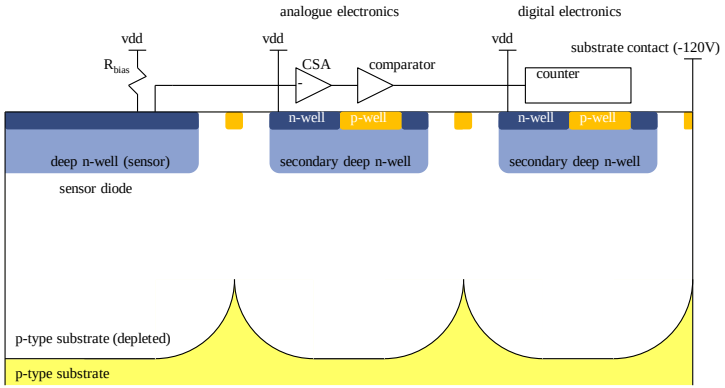
Ionization chambers (ICs) for dose measurement

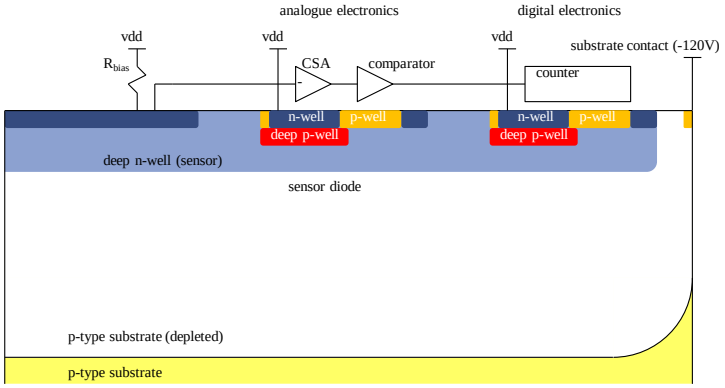
# HIT beam monitor

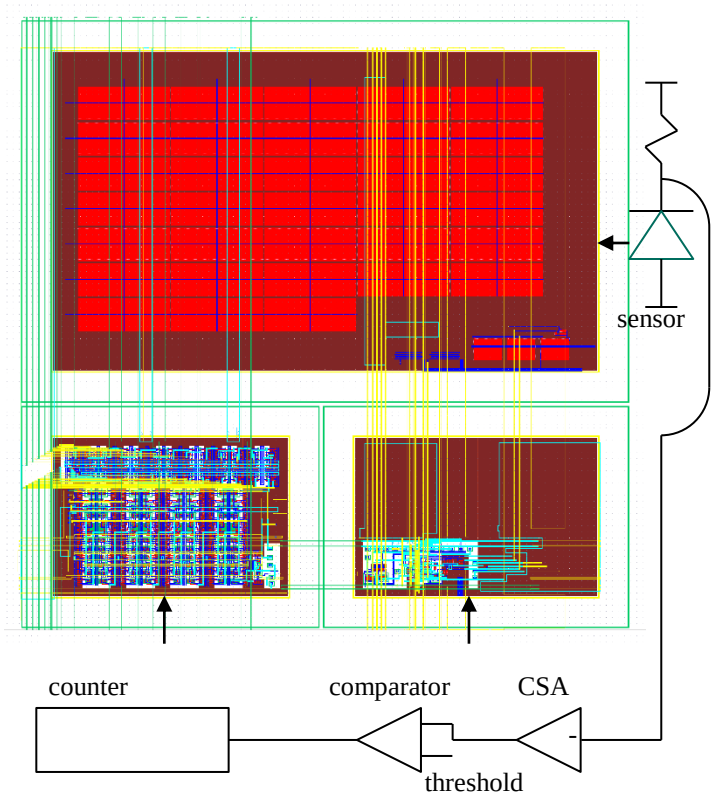
- Goal: Validate feasibility of HV-CMOS technology as beam monitor at Heidelberg Ion-beam Therapy center (HIT)
- Develop a large sensor chip, concepts for interconnection, DAQ, mechanics

- Sensor specifications
- Usable with all light ions (protons to oxygen)
- MR compatibility (magnetic field and acoustic noise during MR scan)
- Dose rates between $1 \cdot 10^6$/s and $2 \cdot 10^{10}$/s
- Position measurement in ≤ 100µs
- Accuracy position ≤ 0.2mm, spot size ≤ 0.4mm FWHM
- Sensitive area ≥ 25x25 cm
- Radiation hardness (clinical use for ≥1 year possible)
- Water equivalent thickness ≤ 2mm (all layers)
- Results (position, spot size) calculated in real time as well as raw data available, generation of interlocks in real time

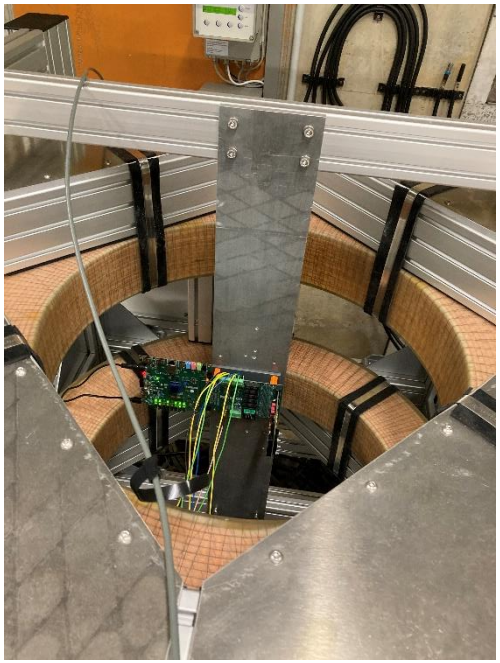
- We have designed several test chips (HITcnt: A. Weber, HITint: H. Mateos) and one 1cm$^2$ prototype (HITcnt2)
- High-rate capability implemented by using hit counters and integrators with high dynamic range
- 3 versions of counting chips with adders to read out x/y-projections at higher speed
- 2 versions of integrating chips
- Matrix sizes 5 x 5 mm²



- Experimental results



Test in magnetic field

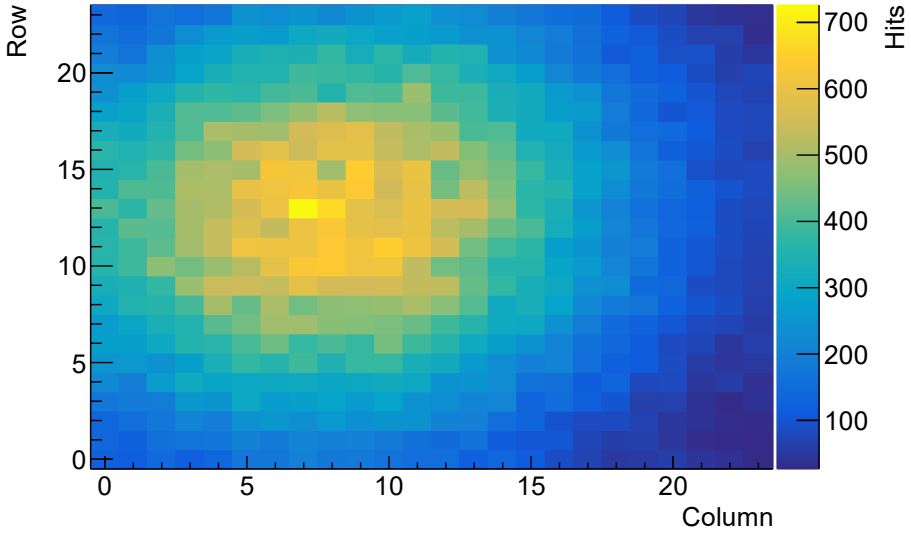
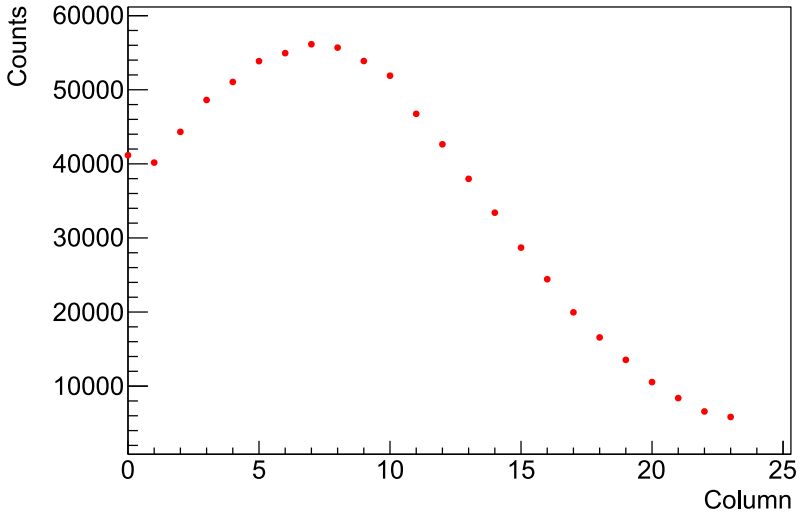
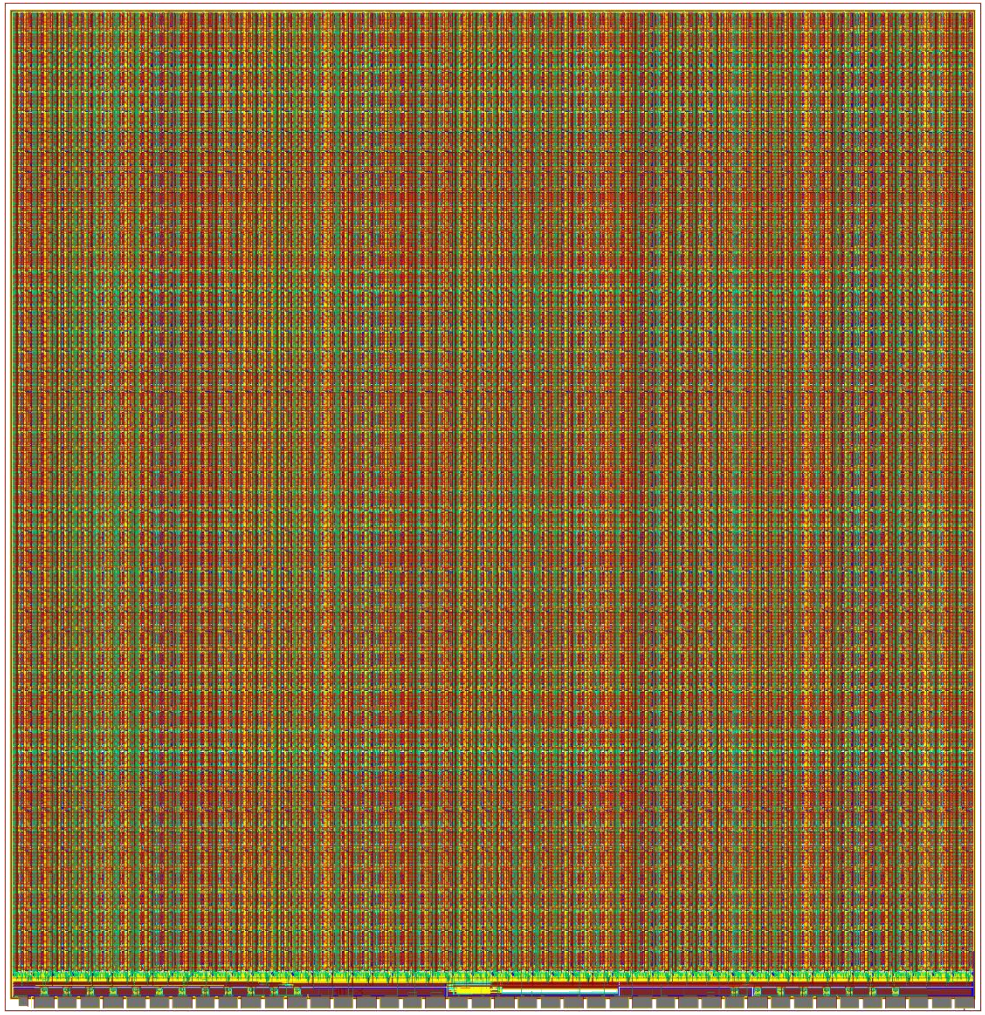


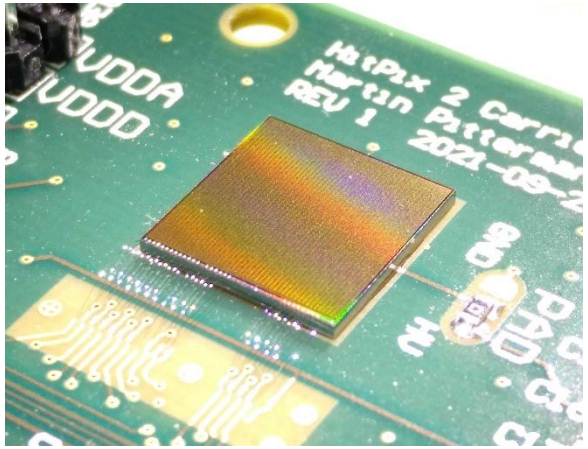

Image of the carbon beam obtained with counters



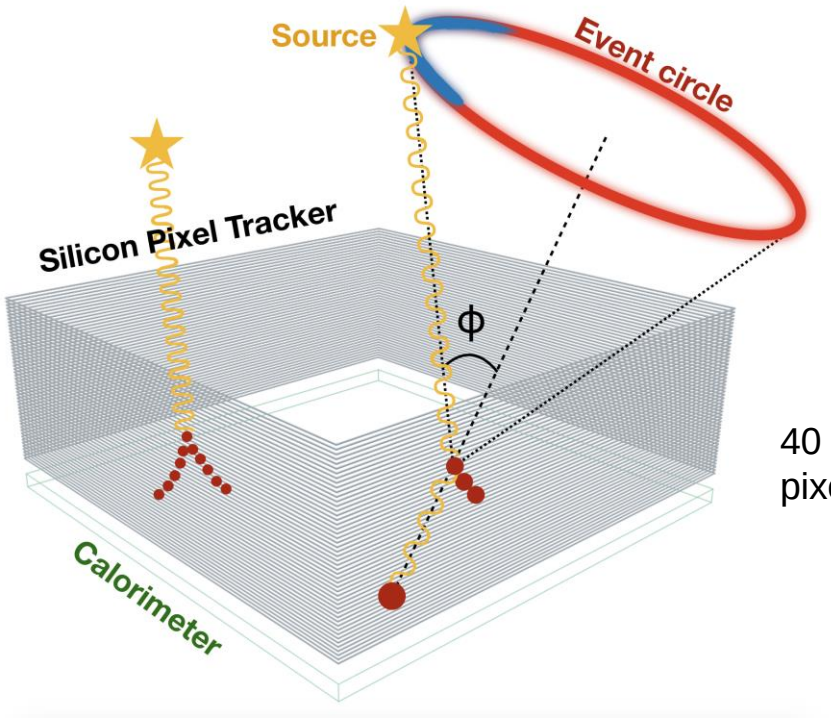

The adders of at the end of each column allow measurement of the beam projection.
The beam intensity was $2 \times 10^6$ carbon ions/s at an energy of 423.44 MeV/u.

- Layout and photo of the HITcnt2





- Sensor for proposed AMEGO-x mission (NASA) – detection of soft (>100keV) to medium (~100MeV) gamma photons from space sources as gamma ray bursts, neutron stars and active galactic nuclei
- Compton scattering and pair production. Compton telescope must be capable of providing 3D tracking data with fine position resolution



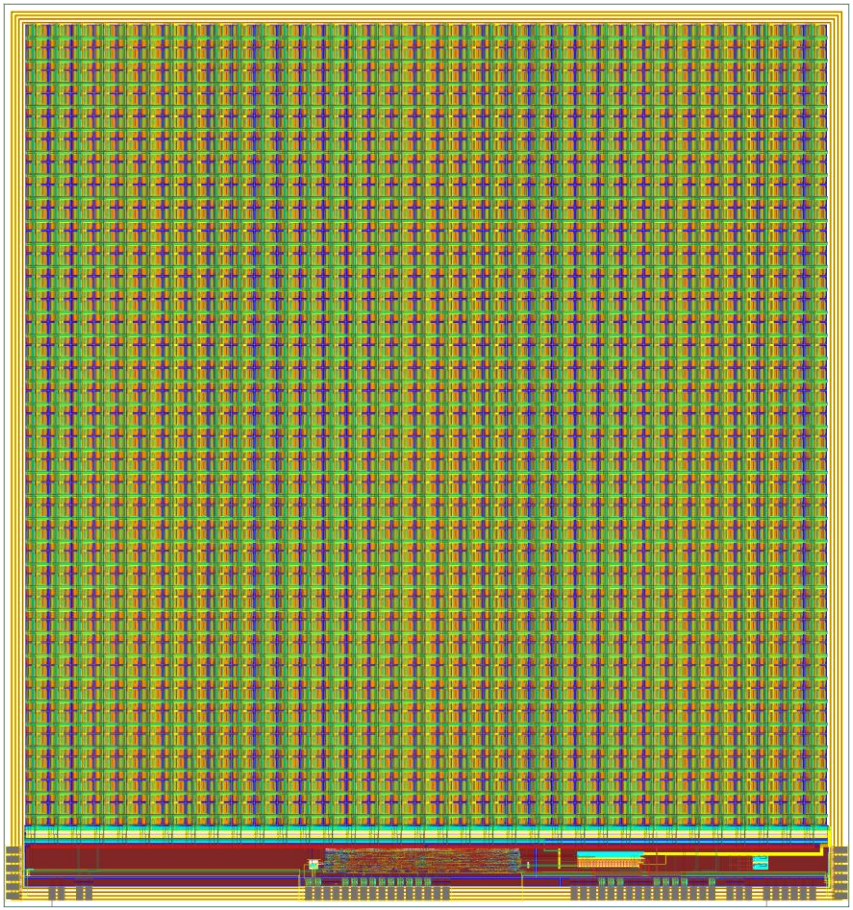

40 layers of monolithic Si pixel detectors

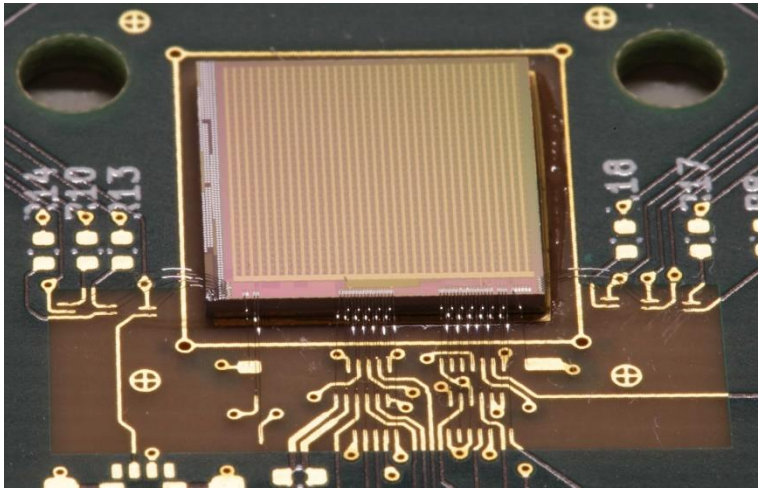
Isabella Brewer et al, Developing the future of gamma-ray astrophysics with monolithic silicon pixels, NIMA, Volume 1019, 11 December 2021, 165795, https://doi.org/10.1016/j.nima.2021.165795

# Compton telescope (AstroPix)

- Specifications for pixel sensors (tracking layers)
- Energy resolution: <10% at 60keV
- Power usage: < 1mW/cm$^2$
- Passive material: < 5% on the active area of Si
- Pixel size: 500 × 500µm$^2$
- Si Thickness: 500µm
- Time stamp: 1µ

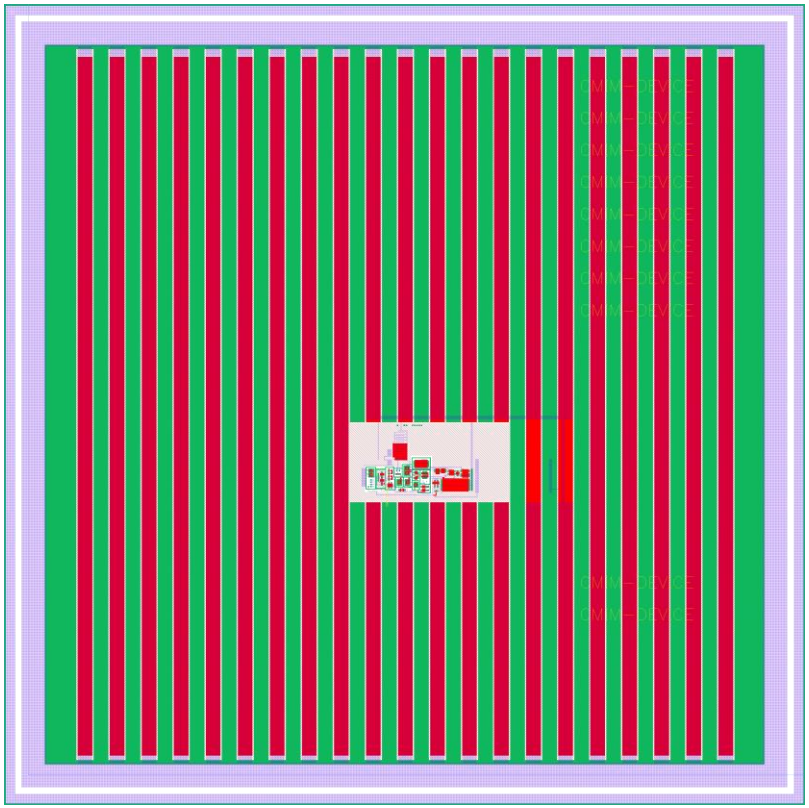
- A sensor called AstroPix

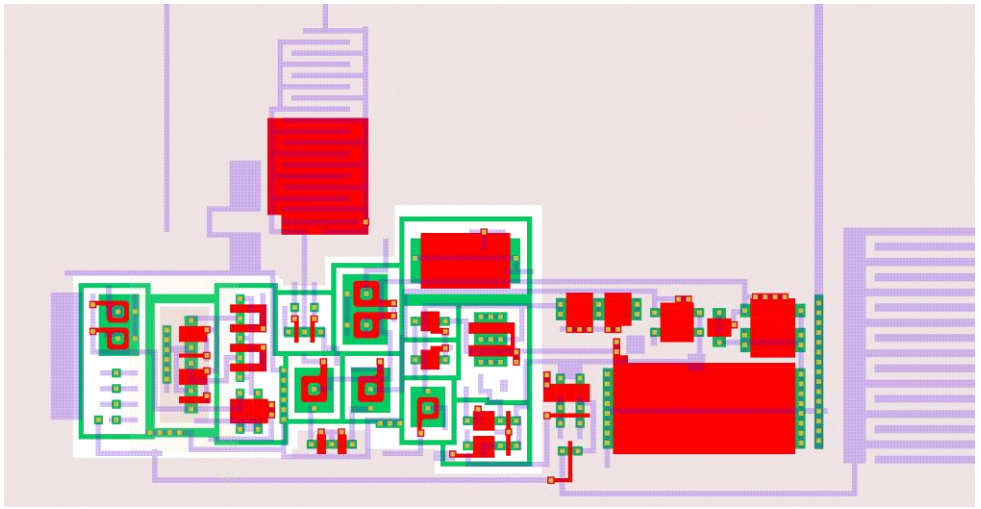




Design: Nicolas Striebig, Richard Leys, Ivan Peric

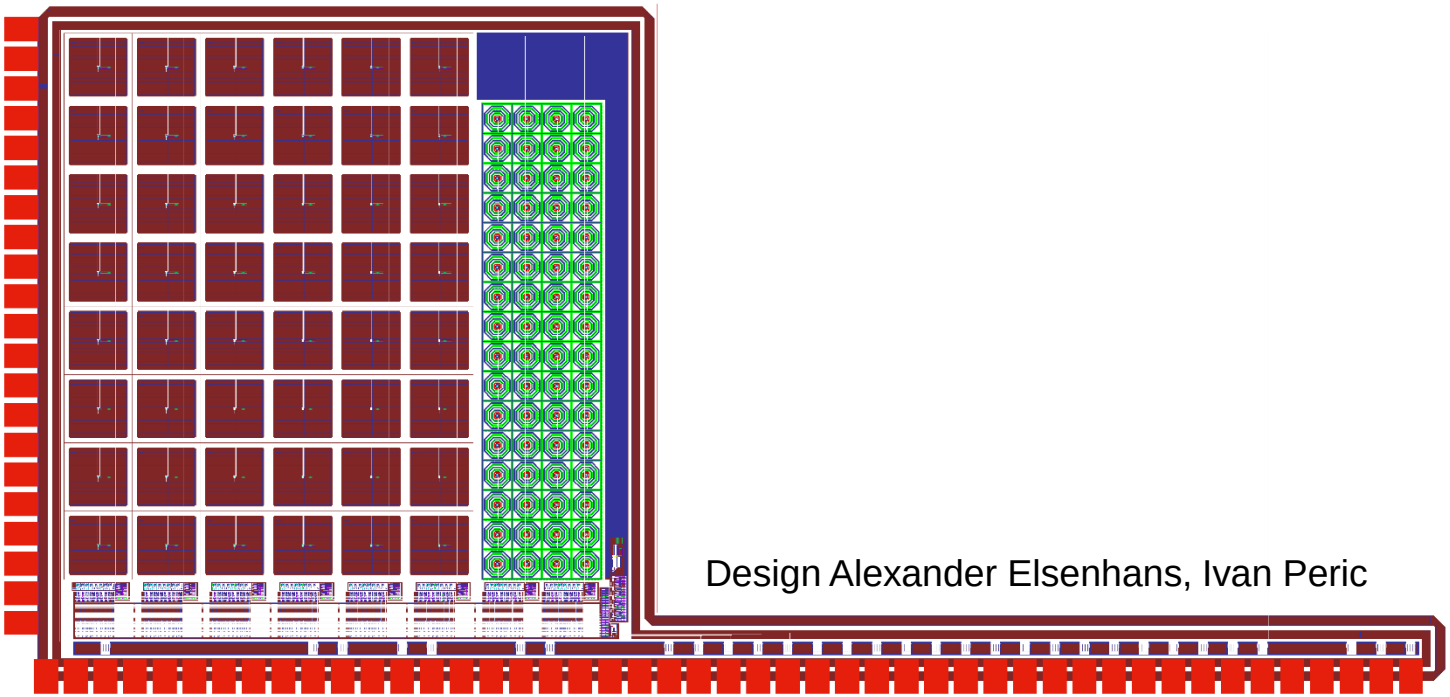
- Pixel size 250 x 250µm
- Very low current consumption ~ 1µA/pixel





# Timing detector with 100ps resolution in SiGe technology of IHP

- Timing sensors for FASER and Mu3e
- Collaboration with the University of Geneva on the development of HV-CMOS sensors in SiGe BiCMOS technology SG13S from IHP
- The technology SG13S allows production of SiGe heterojunction bipolar transistors (HBTs) and CMOS transistors on the same substrate
- Resolutions below 100ps RMS are possible with particle sensors implemented in the IHP process
- Development of HVCMOS timing detector for Mu3e (PicoPix)
- Special amplifier design – no CSA



Design Alexander Elsenhans, Ivan Peric

- Development of HVCMOS pixel sensors for tracking detector of CEPC
- ATLASpix is used as technology demonstrator
- Design of a dedicated sensor in 55nm HVCMOS technology of HLMC

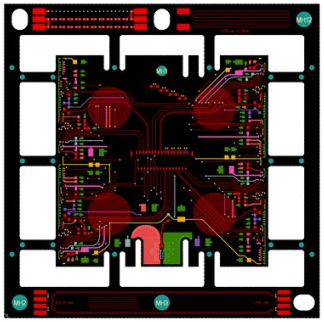


**Fig.** Scheme of the quad module flex.

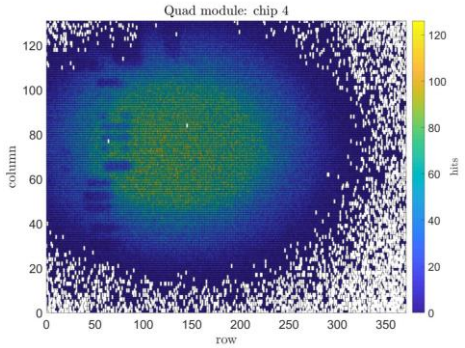



**Fig.** Hit map of a source run with $^{241}$Am on chip 4.

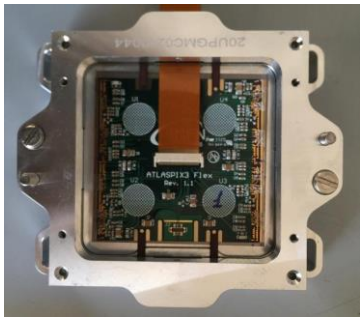
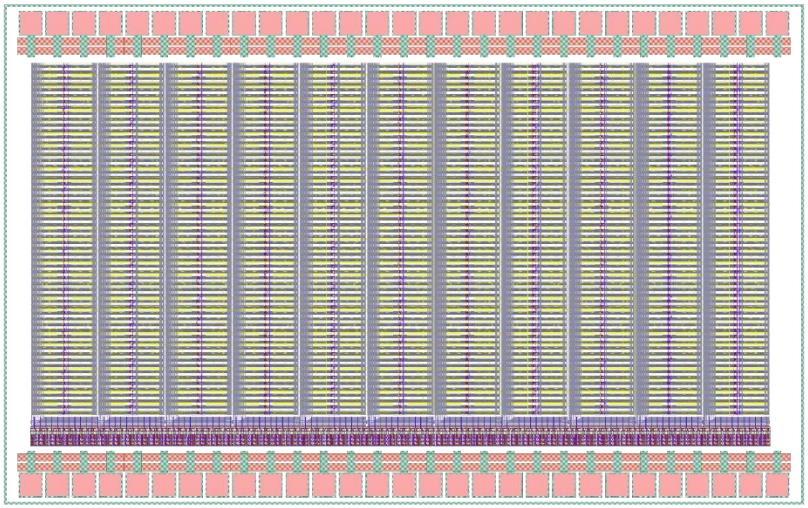
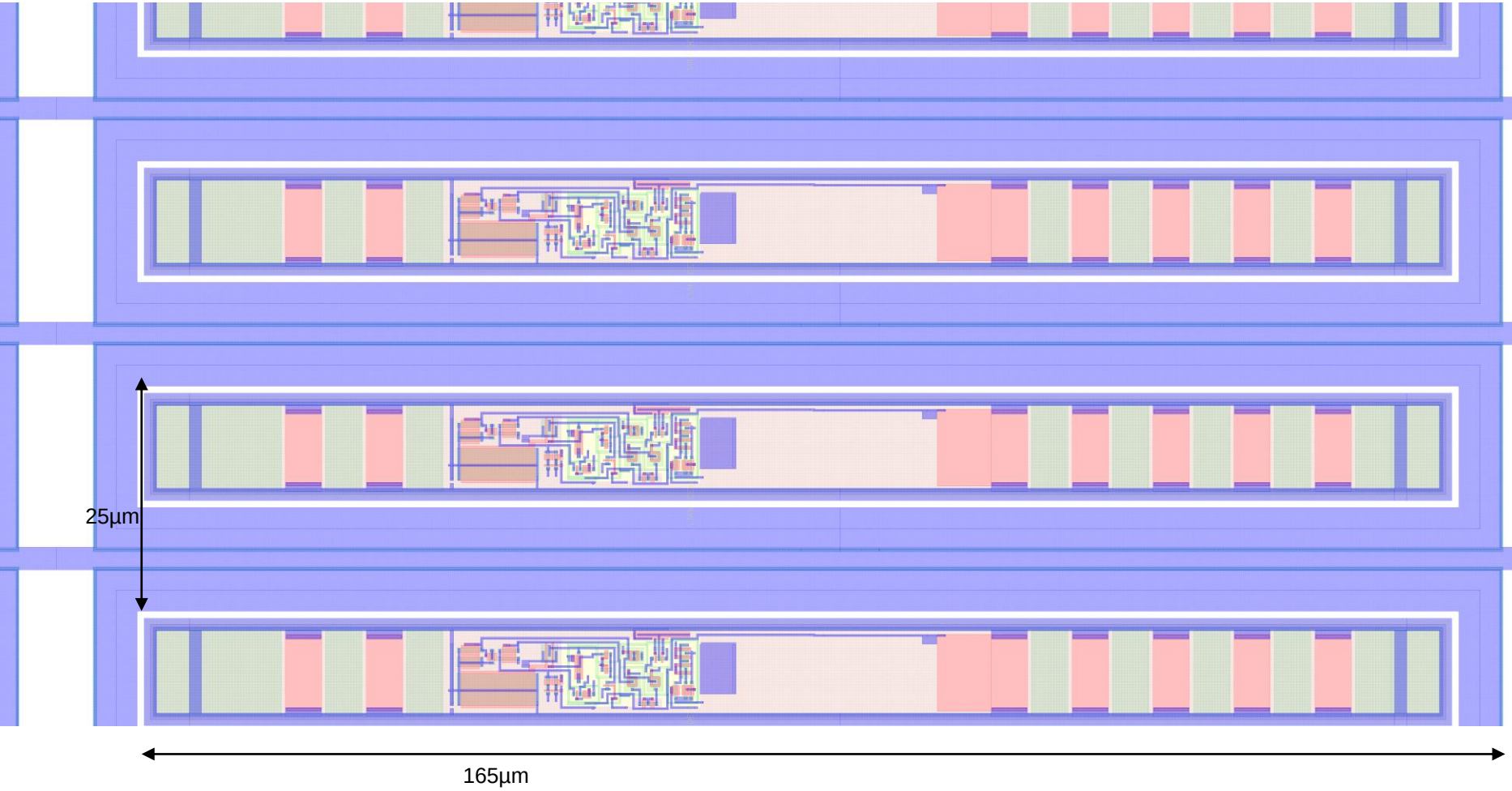


**Fig.** Image of the quad module.

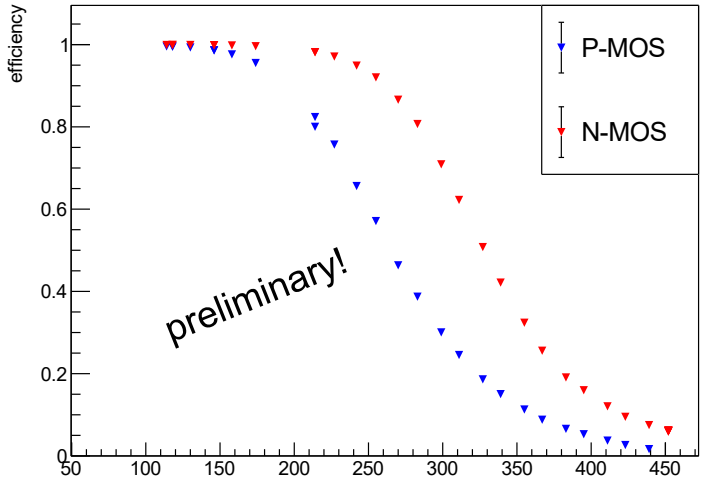
AtlasPix3 quad module Bianca Raciti, PSD 2021

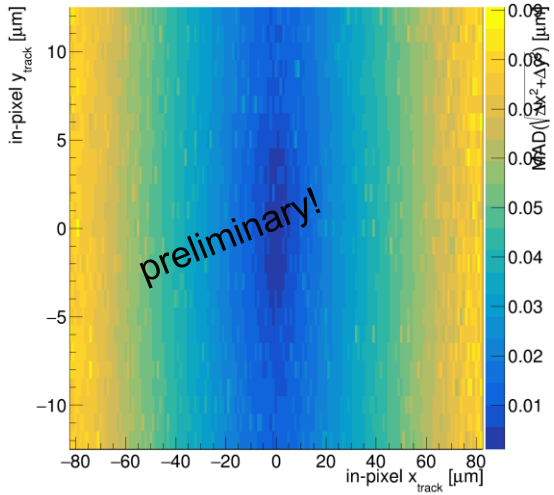


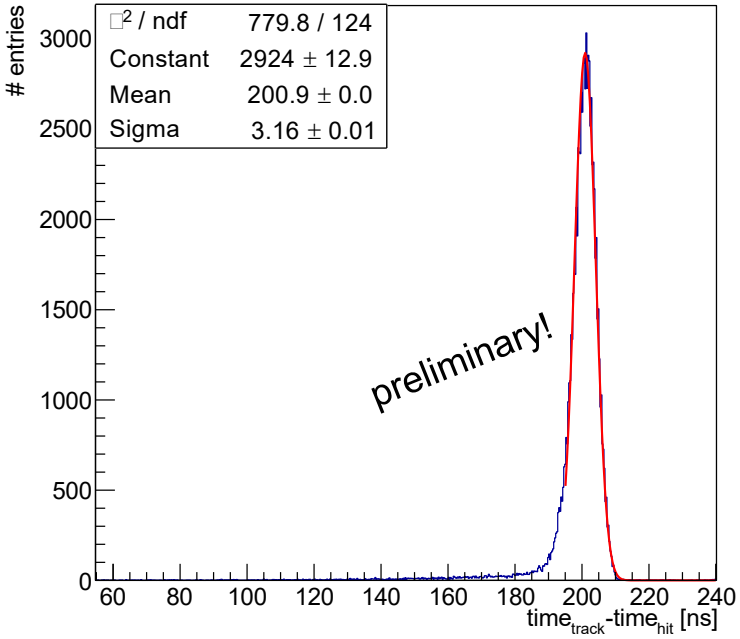
- Sensor for beam telescope - upgrade at DESY - TelePix
- Timing layer for generation of trigger signal
- A TelePix test chip has been produced



- Test beam measurement have been performed at DESY (Lennart Huth)



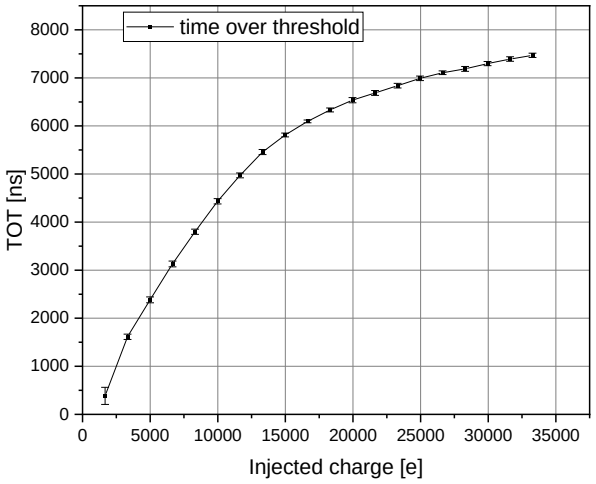



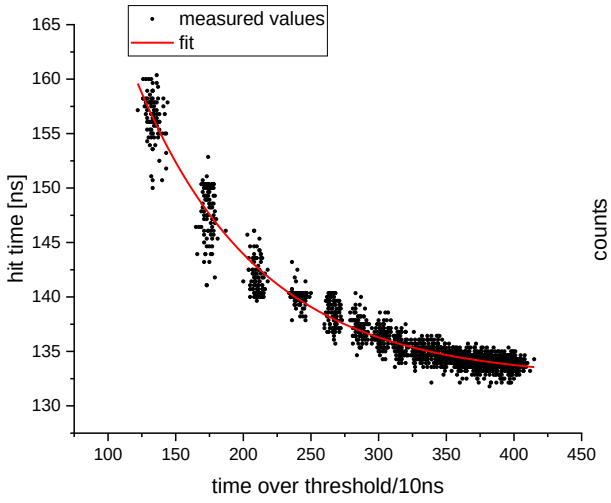



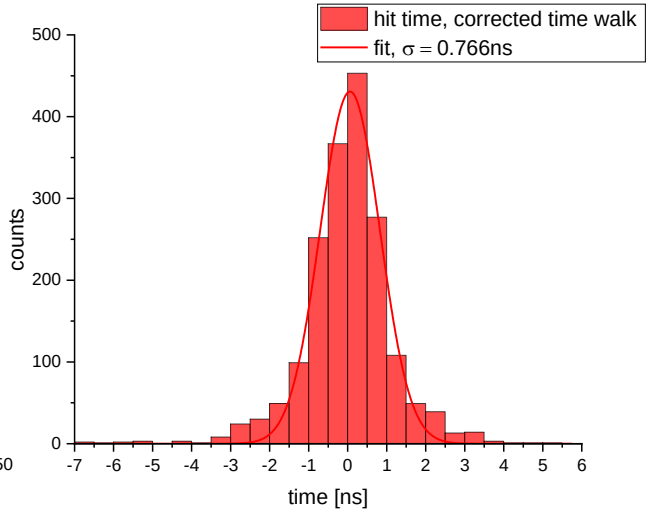

- Y: 165µm pitch -> 47.0µm resolution
- X: 25µm pitch -> 8.2µm resolution

- Time resolution of 3.16ns (RMS) without any correction

- We develop a pixel sensor for PANDA micro-vertex detector (BMBF 05H21VKRD1 )
- Goals:
- Time resolution 1ns
- Sensor area 2cm$^2$
- Pixel size 80µm x 80µm
- Energy measurement in the range to 100ke with noise of 100e for particle identification by dE/dx
- Special amplifier with double gain characteristics
- Fast and slow channel

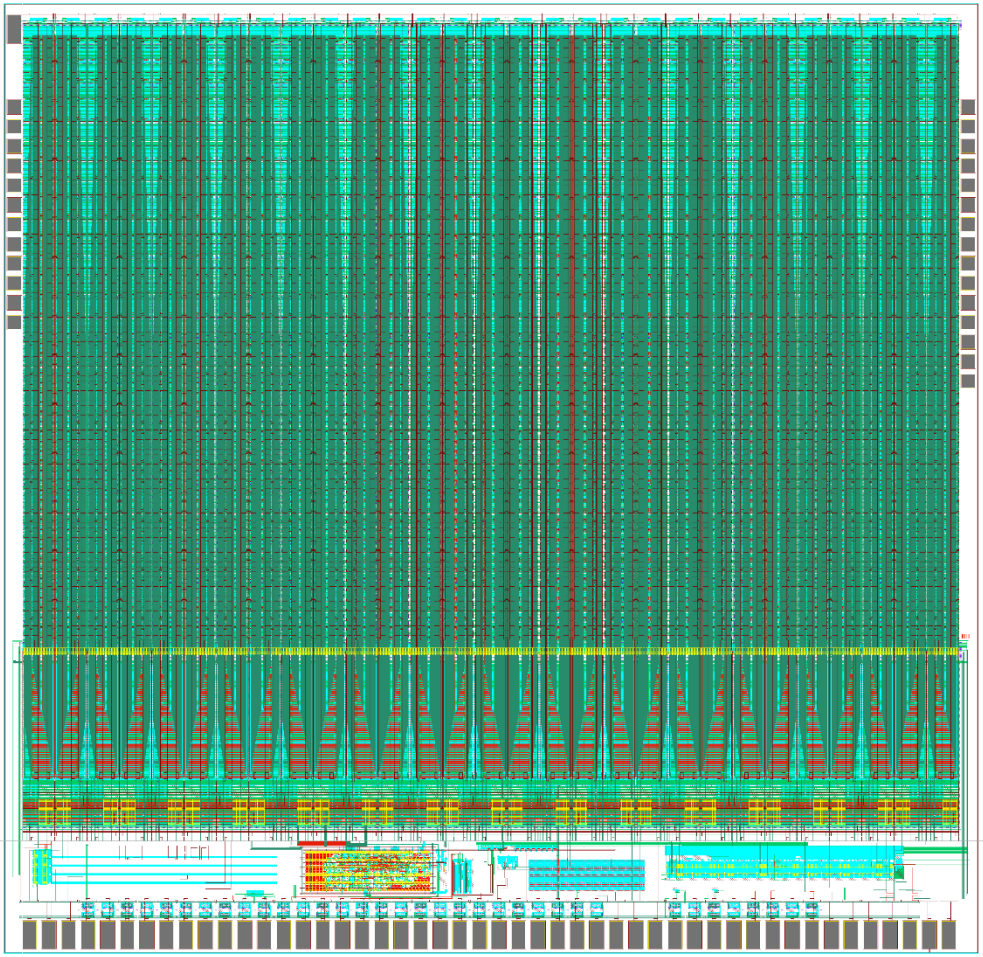


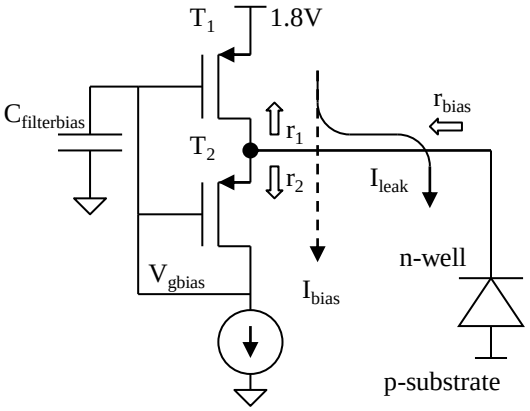
# MightyPix sensor for LHCb upgrade

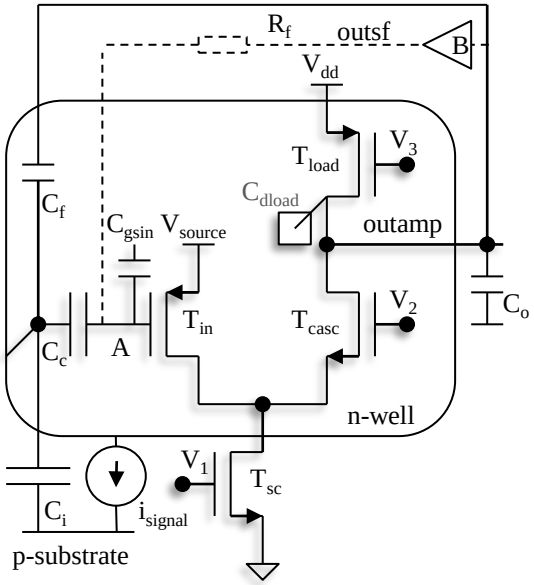
- Development of the HV-MAPS integrated sensor MightyPix for LHCb upgrade Ib/II tracker
- The submission of first large prototype is planned for March 2022
- Sigrid Scherl, Nicolas Striebig, Richard Leys

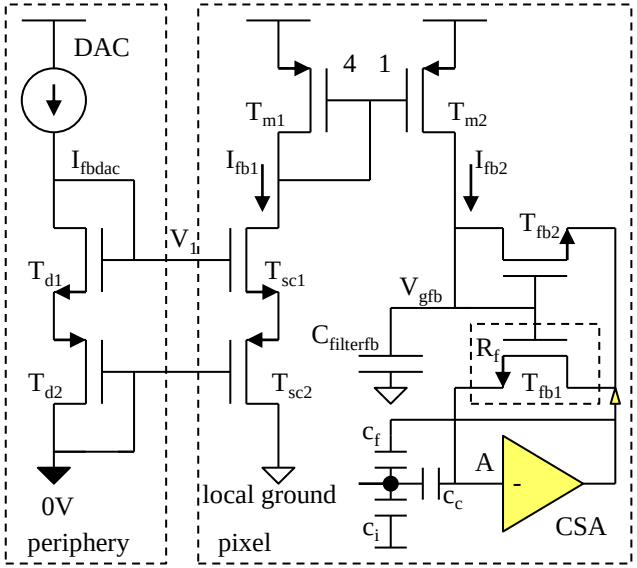


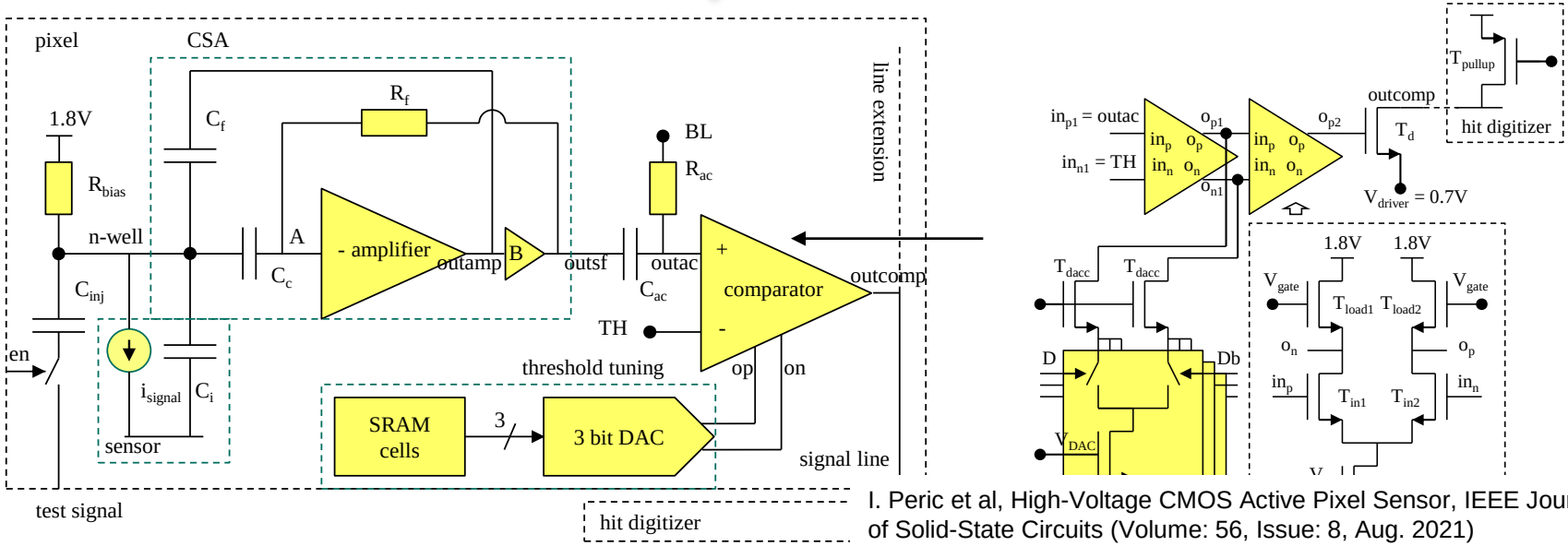
Test chip from run 2020

- Summary
- HVCMOS sensors and applications
- Mu3e
- HIT beam monitor
- Compton telescope (AstroPix)
- Timing detector with 100ps resolution in SiGe technology of IHP
- CEPC
- Sensor for beam telescope
- PANDA micro-vertex detector
- MightyPix sensor for LHCb upgrade




I. Peric et al, High-Voltage CMOS Active Pixel Sensor, IEEE Journal of Solid-State Circuits (Volume: 56, Issue: 8, Aug. 2021) https://doi.org/10.1109/JSSC.2021.3061760