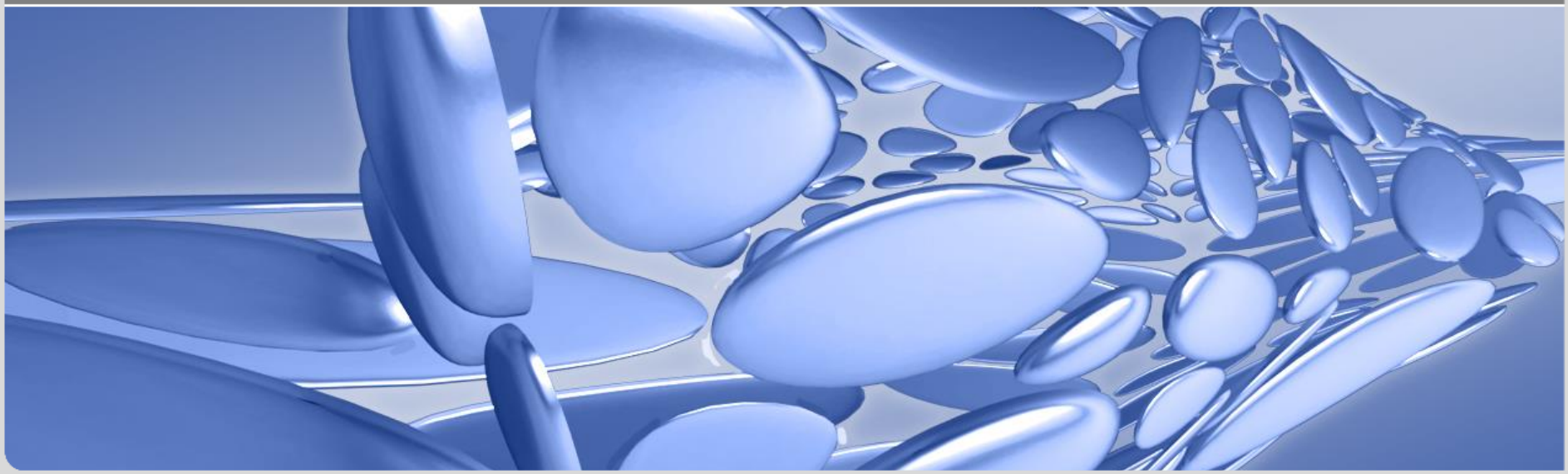
HVCMOS Sensors for high rate particle tracking



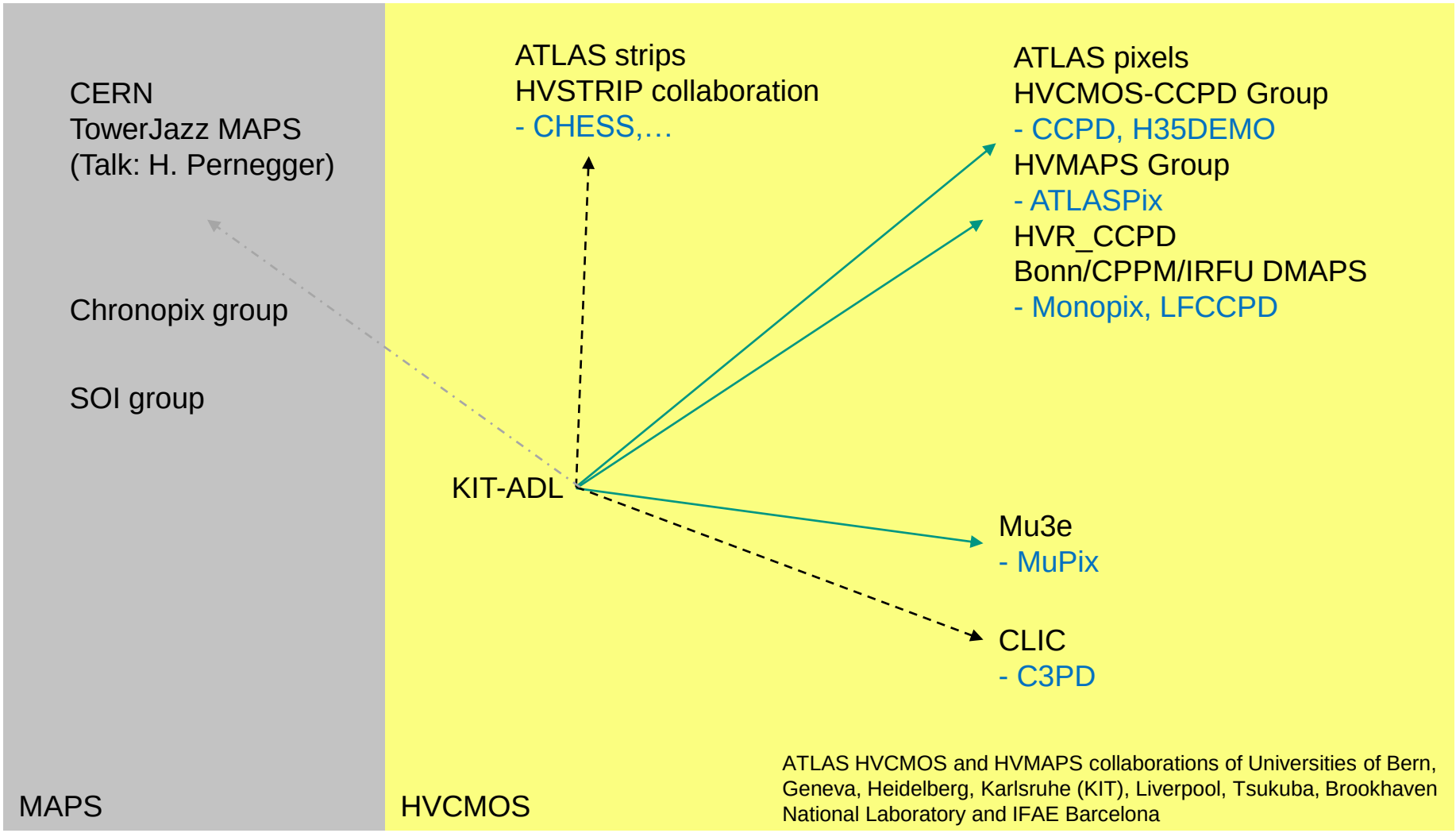
- High rate particle tracking -> fast charge collection, fast readout, high time resolution, high radiation tolerance
- HVCMOS, monolithic and hybrid detectors (based on capacitive coupling)
- Introduction – HVCMOS, monolithic, CCPD, experiments, groups, our group
- Applications: ATLAS and Mu3e – specifications
- Small sensors – results
- Large sensors
- H35DEMO – some results
- Monolithic Sensors in AMS H18 and LFA15
- Example MuPix8 – basic
- ATLASPix – more features
- Readout types
- Pixel forms
- Address compression for triggered readout
- Analog measurements and time-walk
  (for triggerless readout)
- Experimental Results

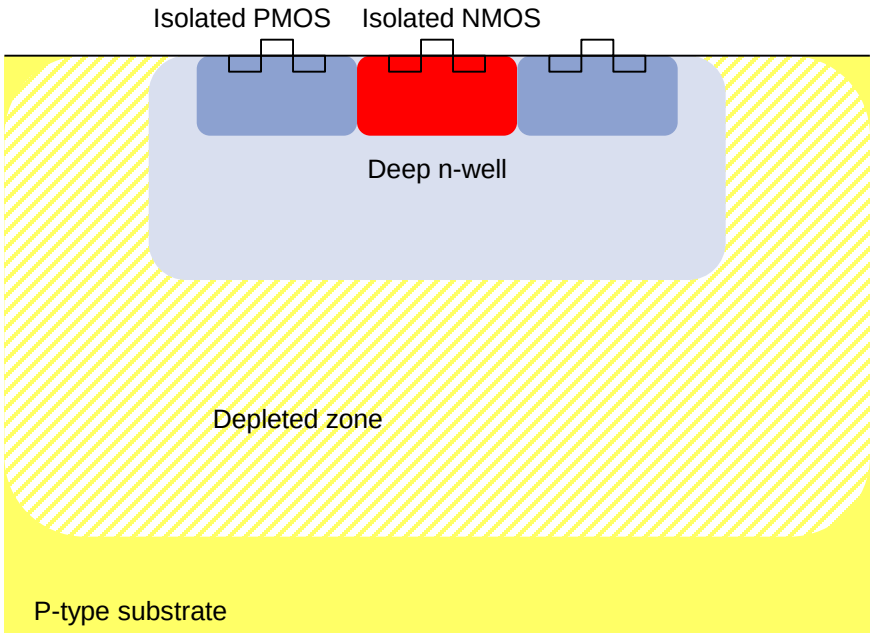
- HVCMOS Sensors for MU3E, ATLAS, CLIC
- HVCMOS Talks

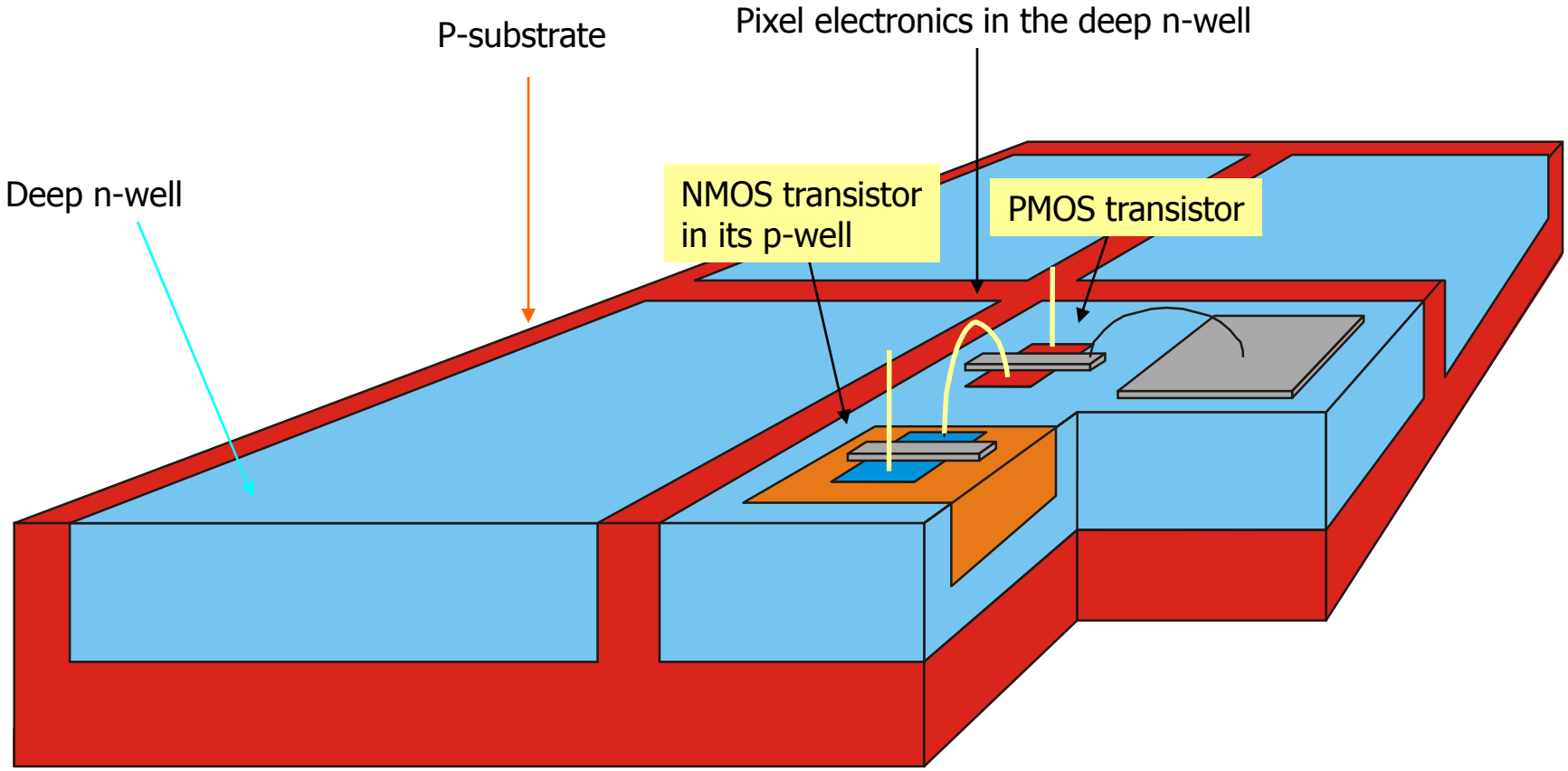
ATLAS
Eva Vilella: Development of HV-MAPS detectors at the University of Liverpool
Thomas Weston: An overview of recent HV-CMOS results

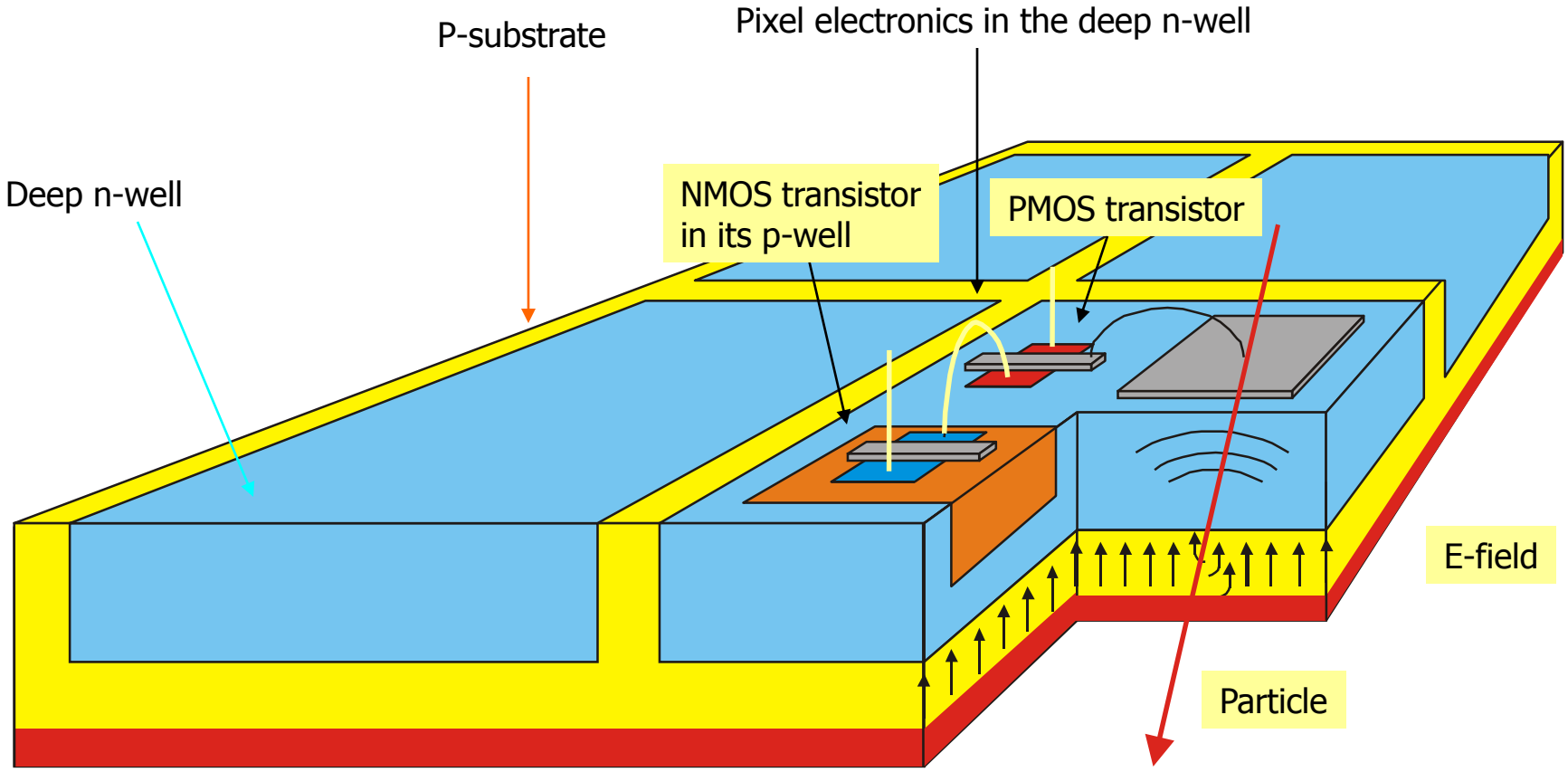
CLIC
Daniel Hynds: HV-CMOS developments for the CLIC vertex detector

- Depleted-MAPS developments

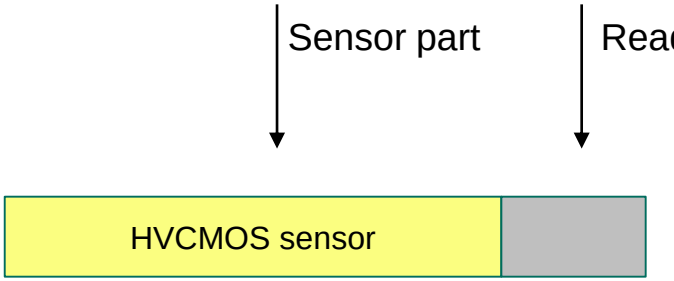



Isolated PMOS
Isolated NMOS
Deep n-well
Depleted zone
P-type substrate

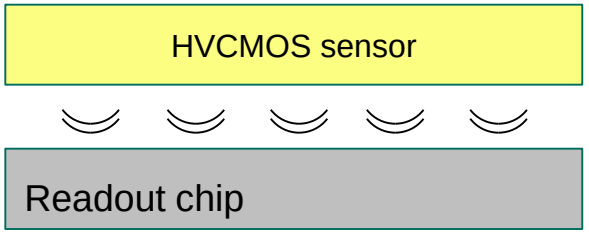

P-substrate
Pixel electronics in the deep n-well
Deep n-well
NMOS transistor
in its p-well
PMOS transistor


P-substrate
Pixel electronics in the deep n-well
Deep n-well
NMOS transistor
in its p-well
PMOS transistor
E-field
Particle

- CCPD vs. Monolithic

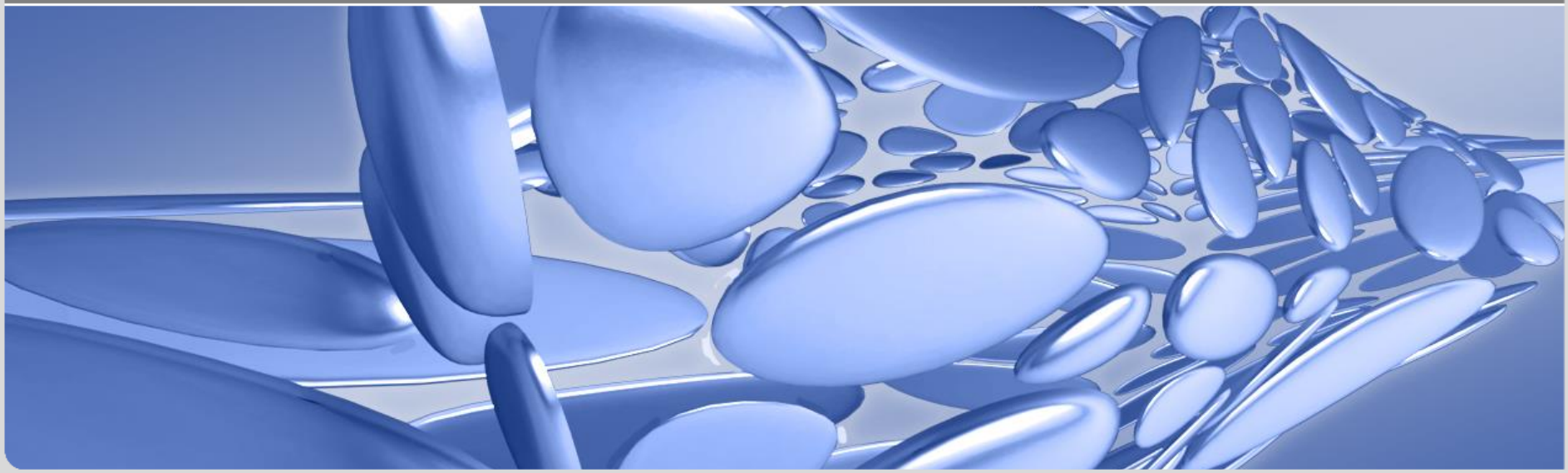


Monolithic



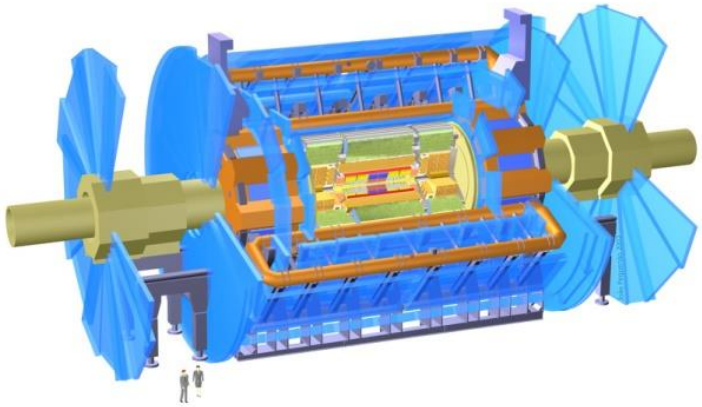
Capacitive coupled pixel detector - CCPD

ATLAS and Mu3e Sensors

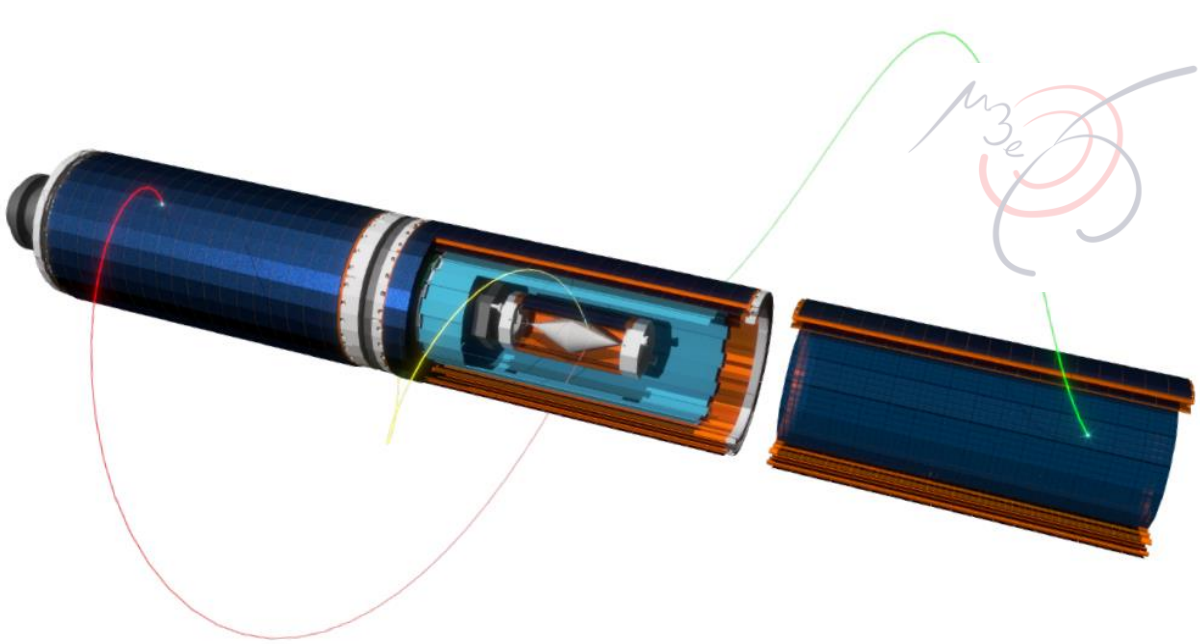


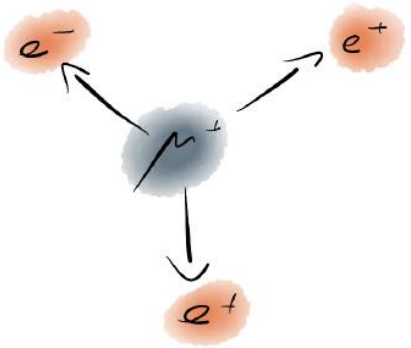
Specifications

- Specifications for ATLAS HL pixel detector
- Particle flux:
- Layer 1 (4cm) 50 hits/cm^2/BC (BC = 25ns)
- Layer 3 (14cm) 5 hits/cm^2/BC
- Layer 5 (30cm) 1 hits/cm^2/BC
- Triggered readout
- Radiation tolerance ~ 0.7 to 2 x 10^{15} neq/cm2, ~ 30 to 100MRad (3rd /5th layer)
- Pixel size 50um x 50um for 3rd layer, may be larger for outer layers and smaller for inner layers
- Power consumption < 500mW/cm^2
- Present goal: 99% of the hits must be detected with timing better than 50ns, later 25ns
- Noise level 10^{-4}hits/BC

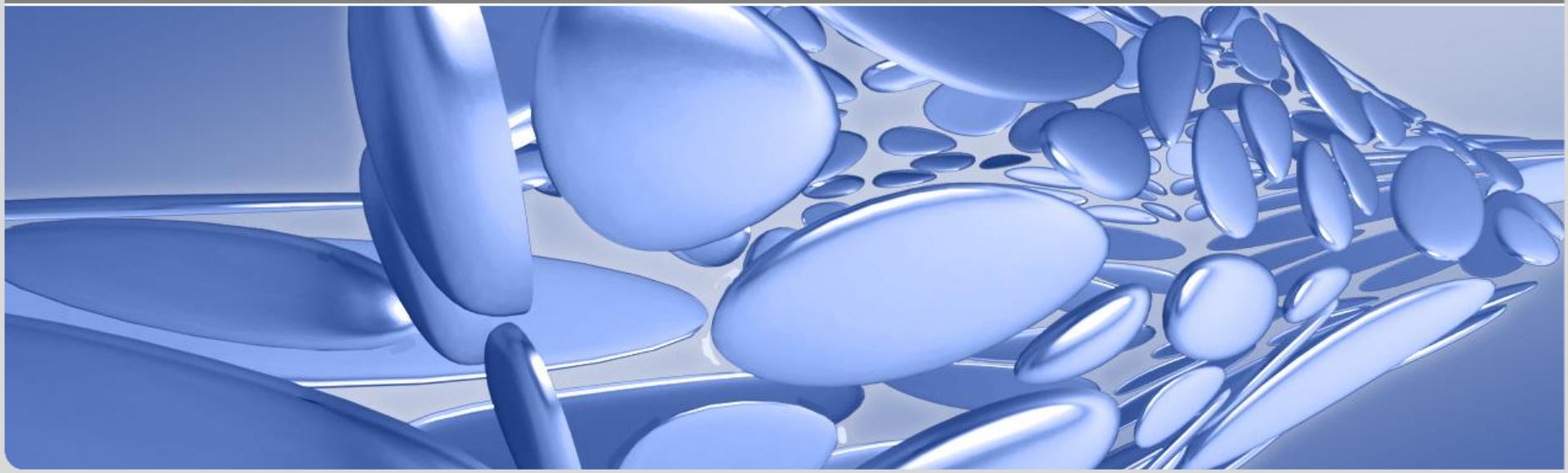


- Concept: thin silicon pixel HVCMOS detector and timing detectors (scintillating fibres and tiles)
- Specifications for Mu3e pixel detector
- Momentum resolution 0.5 Mev/c, vertex resolution ~ 200um
- Particle flux: 10^9 muon decays / s -> 1.5M hits/s/cm^2 (like 0.04 hits/BC/cm^2), all hits are readout, no trigger
- Target sensitivity 1 in 10^{16} decays
- Radiation tolerance ~ NA
- Pixel size 80um x 80um
- Low momentum particles: < 53 MeV/c, momentum resolution 0.5 Mev/c -> detector thickness ~ 50um
- Cooling with helium -> power consumption < 200mW/cm^2

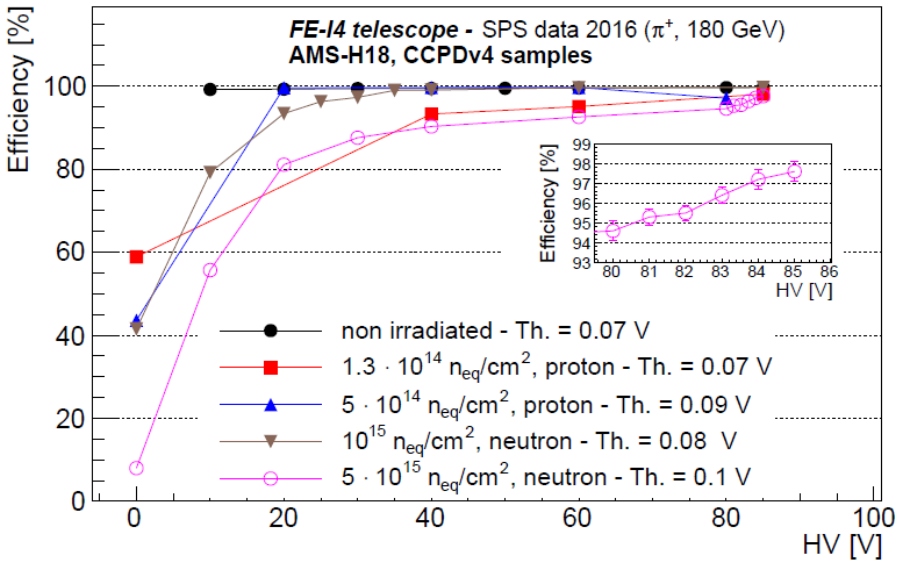




Small sensors



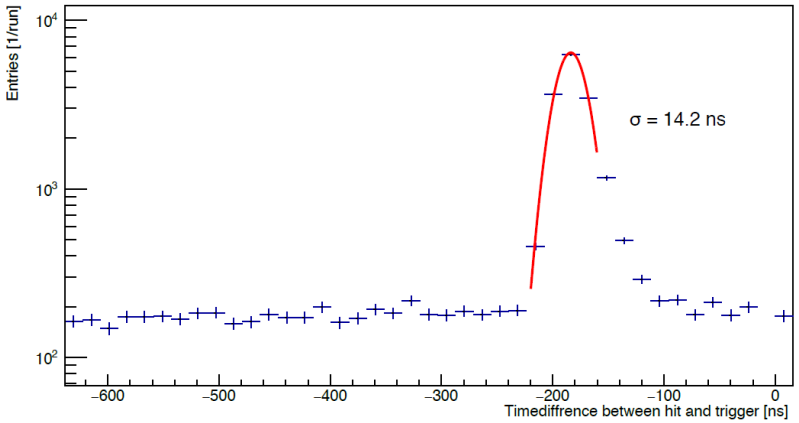
- HVCMOS CCPD sensors implemented in AMS H18 technology on standard 10 Ω cm substrate (CCPDv4) have been irradiated to fluences between 1.3 x 10^{14} and 5·x 10^{15} n_{eq}/cm^2 and tested in beam (full matrix test). The average hit efficiencies of from 97.6 % (highest fluence) to 99.7% have been measured. These values are comparable to hit efficiencies of planar pixel sensors.
- More details: Thomas Weston: An overview of recent HV-CMOS results



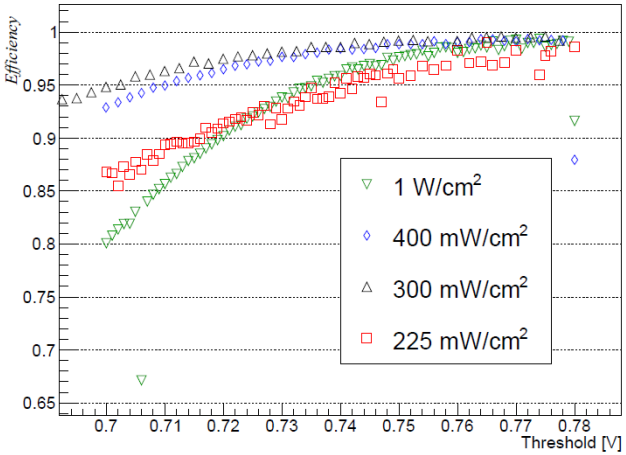
CCPDv4: *Measured detection efficiencies in the beam test versus applied bias voltage.*

M. Benoit et al.,
"Testbeam results of irradiated AMS H18 HV-CMOS pixel sensor prototypes"
arXiv:1611.02669 [physics.ins-det]

- HVCMOS monolithic sensors implemented in AMS H18 technology on standard 10 Ωcm substrate (MuPix7)
- On chip readout, fast data transmission (up to 1.6 Gbit/s)



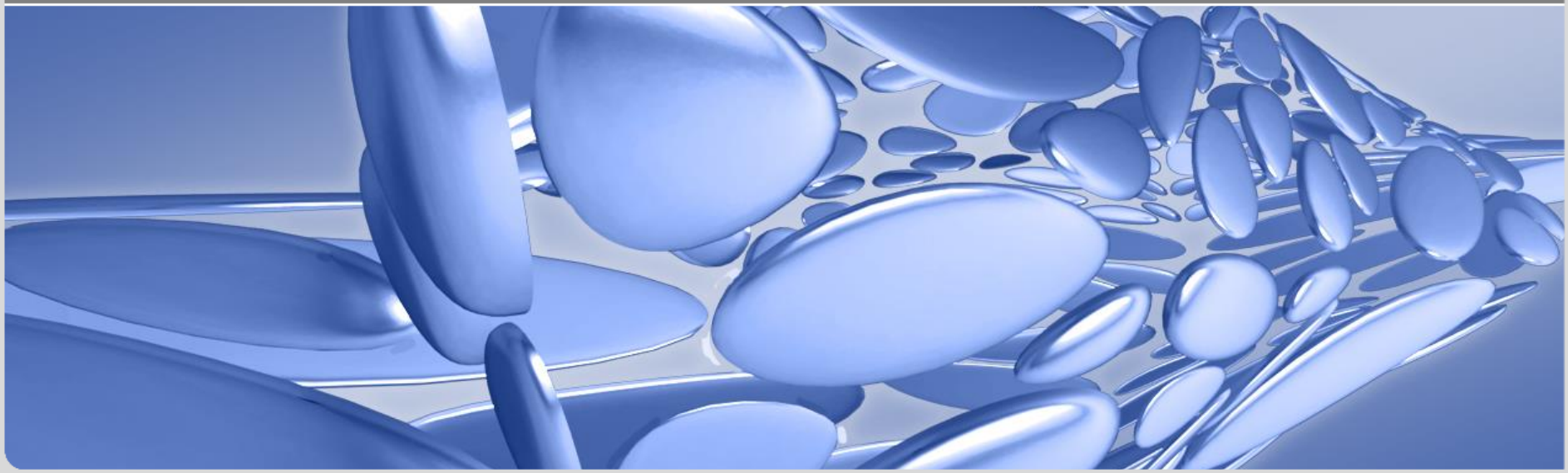
Timing resolution measured using settings with a power consumption of 300W/cm^2. Shown is the difference in time between the hit in the DUT and the scintillators. Bin size is 16 ns. Measured at DESY



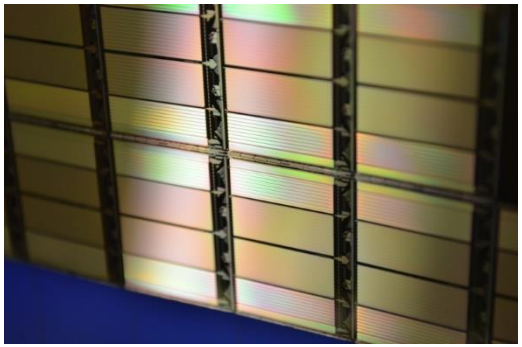
Efficiency as function of threshold for different power settings. Measured at PSI

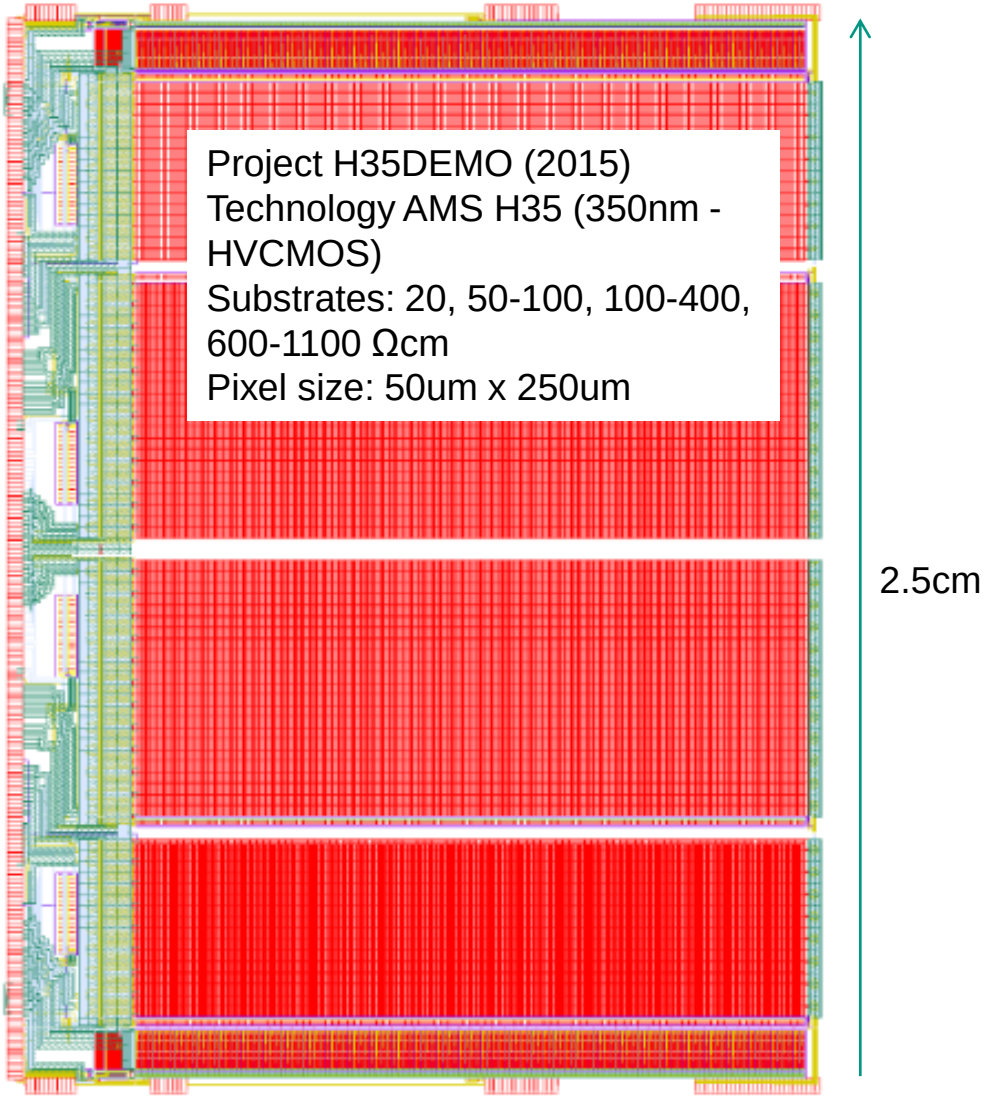
H. Augustin, MuPix7 – A fast monolithic HV-CMOS pixel chip for Mu3e, JINST, Pixel 2016

Large sensors

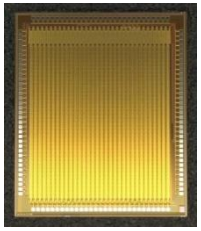


- …





CCPD (1-8)

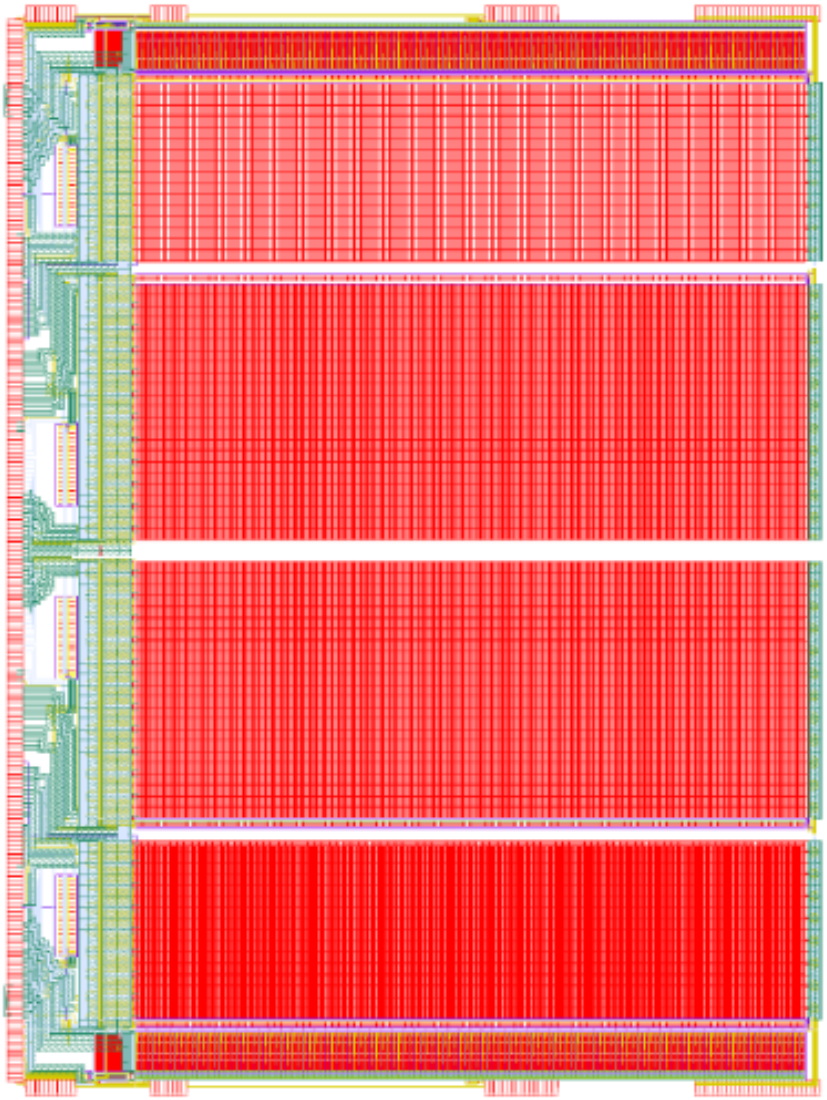


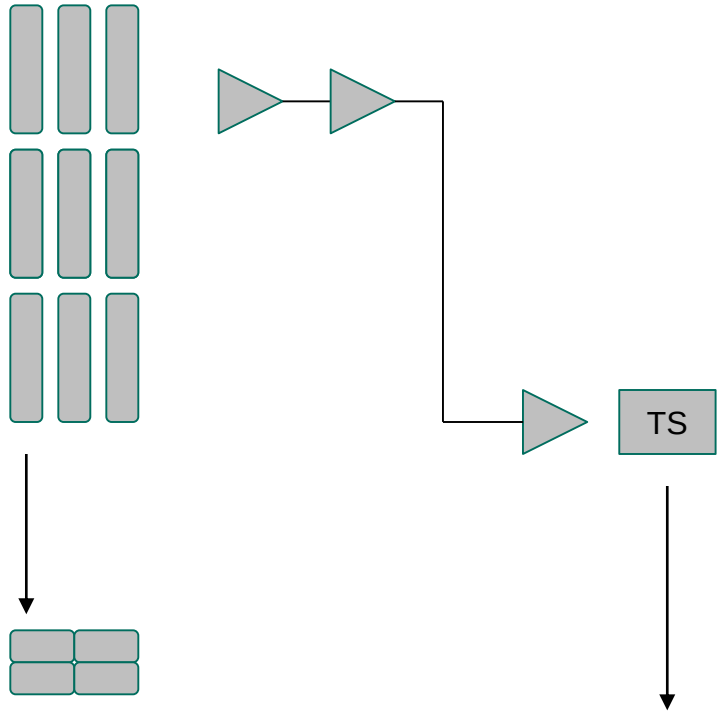
MuPixel 7

H35DEMO

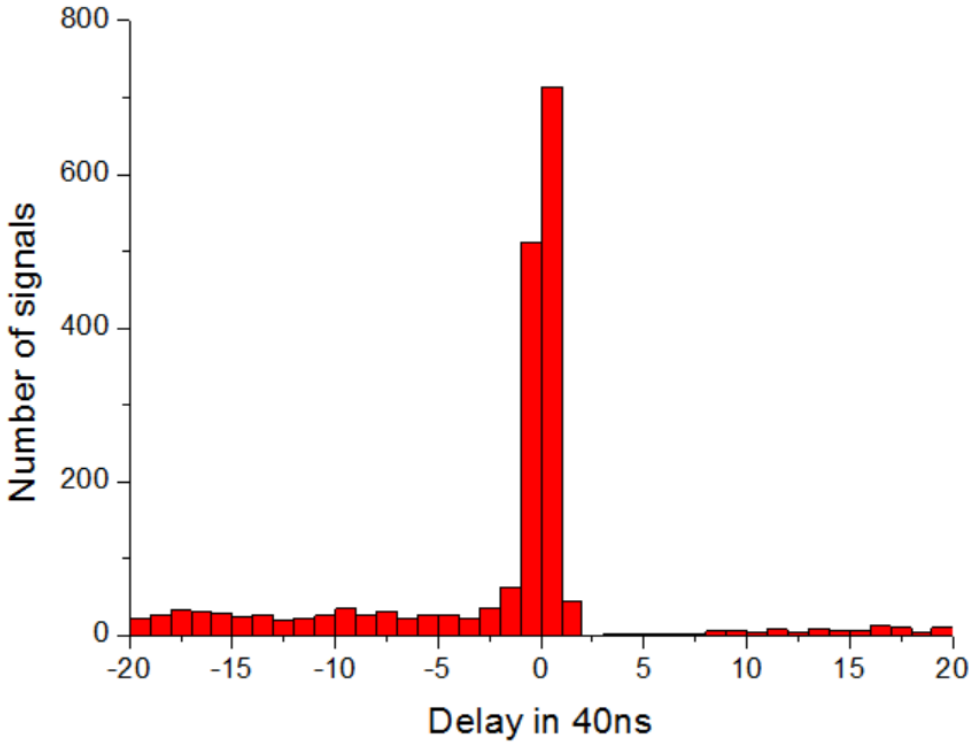
- H35DEMO
- -> Talks
- Eva Vilella: Development of HV-MAPS detectors at the University of Liverpool
- Thomas Weston: An overview of recent HV-CMOS results

- …



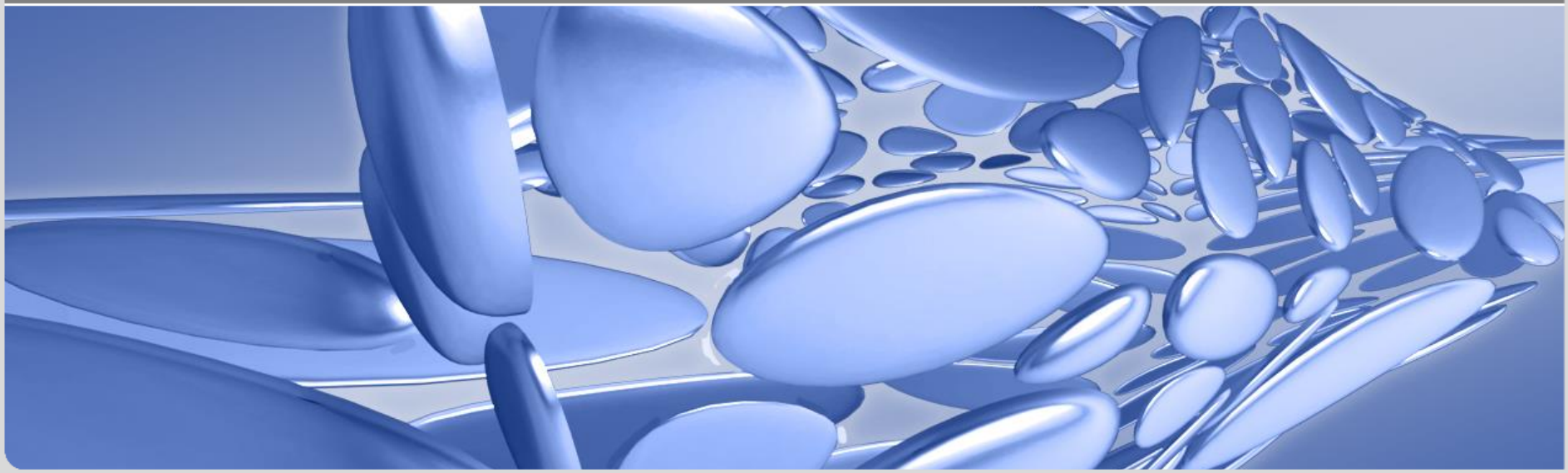

TS

- The H35DEMO has the possibility can be readout as a monolithic sensor
- Zero suppression and time measurement on chip
- TWCC



Time resolution – difference between the time stamp and the trigger moment

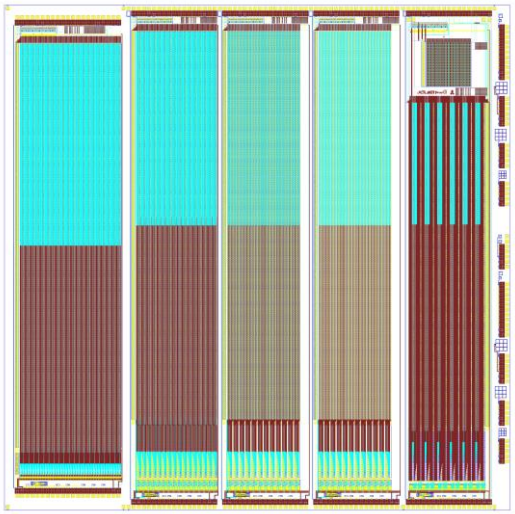
Large monolithic sensors in DSM technologies



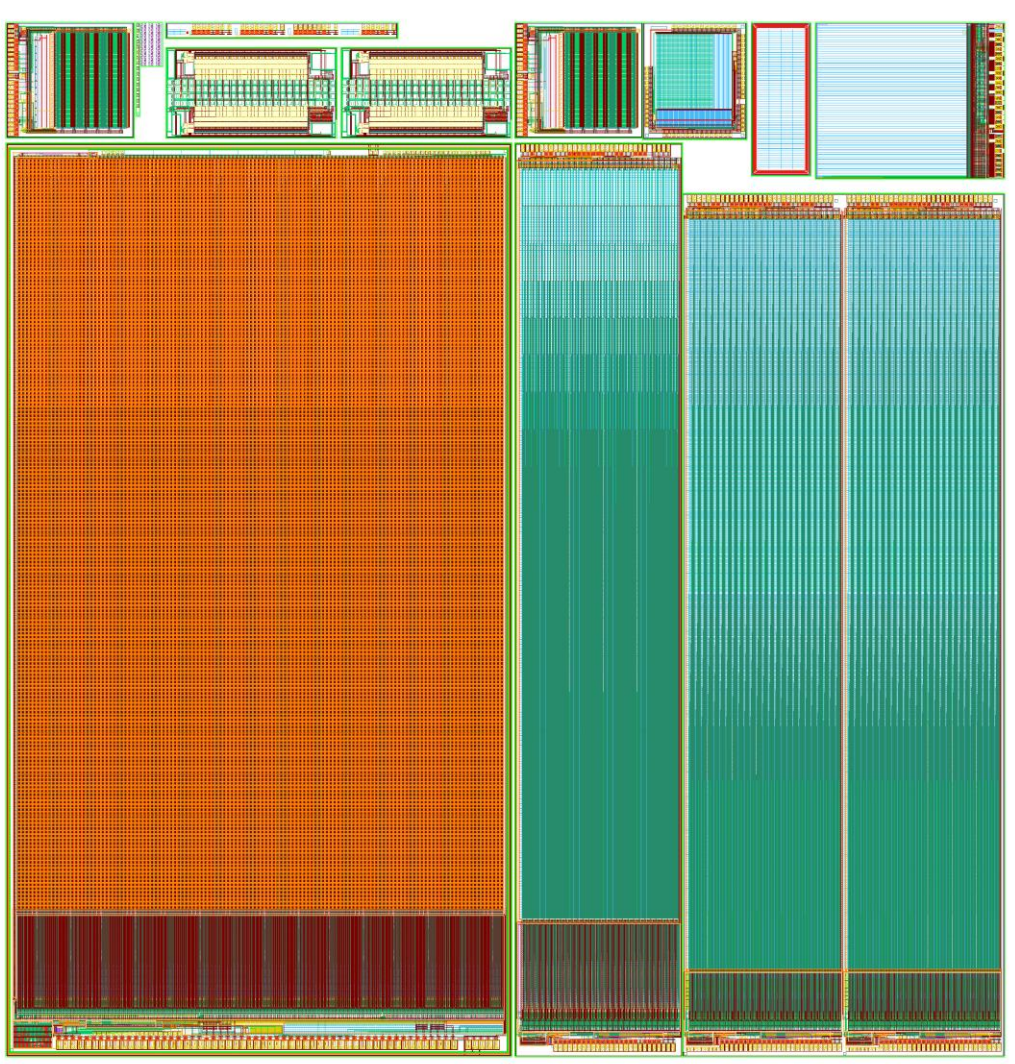
- …

Project MuPix8/ATLASPix (2016)
Technology AMS aH18 (180nm)
Substrates: 20, 50-100, 100-400, 600-1100 Ωcm
4-well HVCMOS process

Project LF_ATLASPix (2016)
Technology LFA15 (150nm)
Substrates: 100, 500-1100, 1900, 3800 Ωcm
4-well HVCMOS process

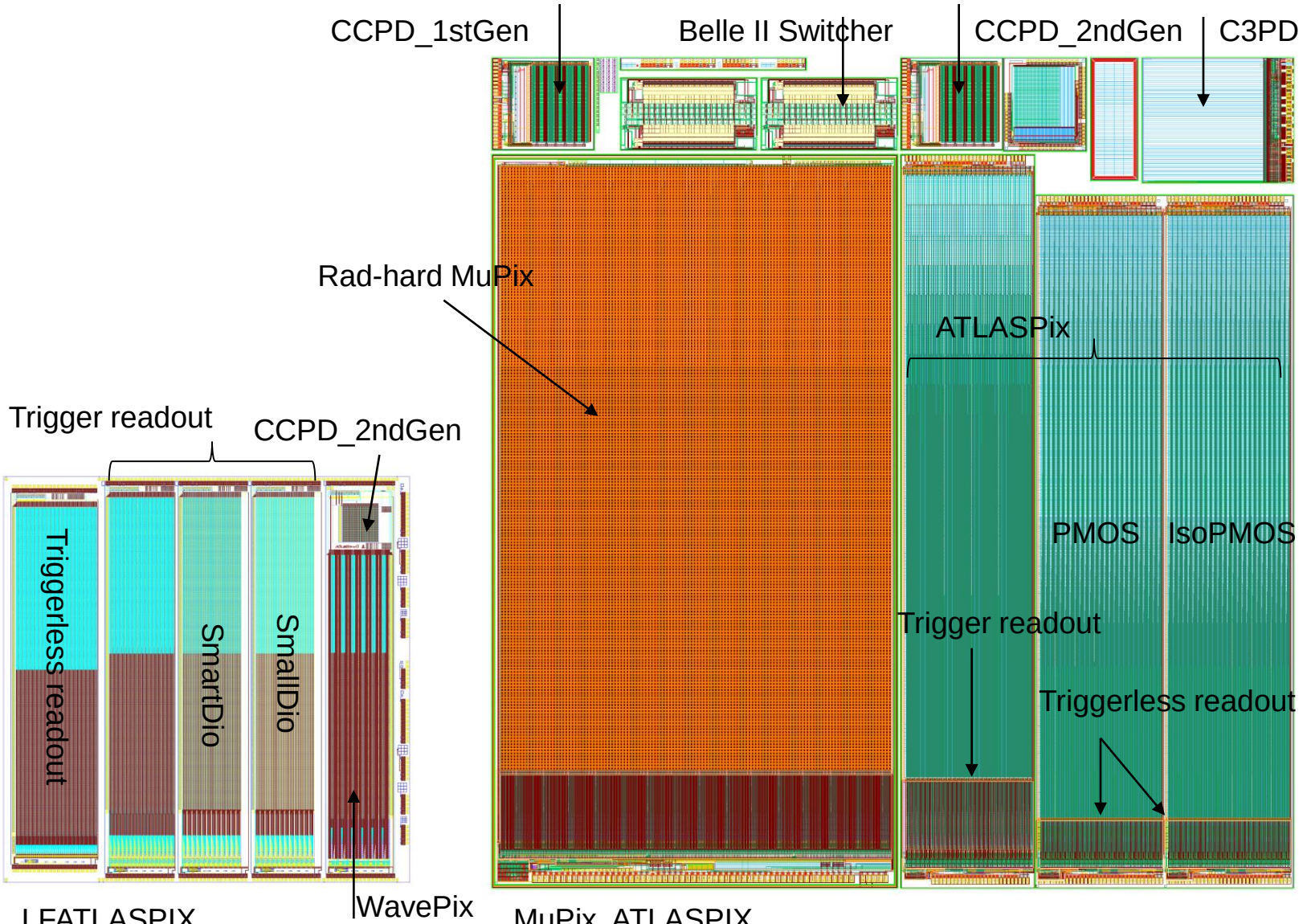


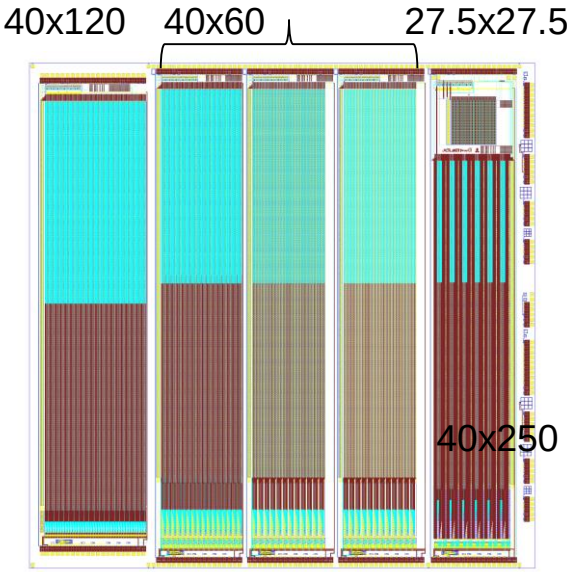
LFATLASPIX



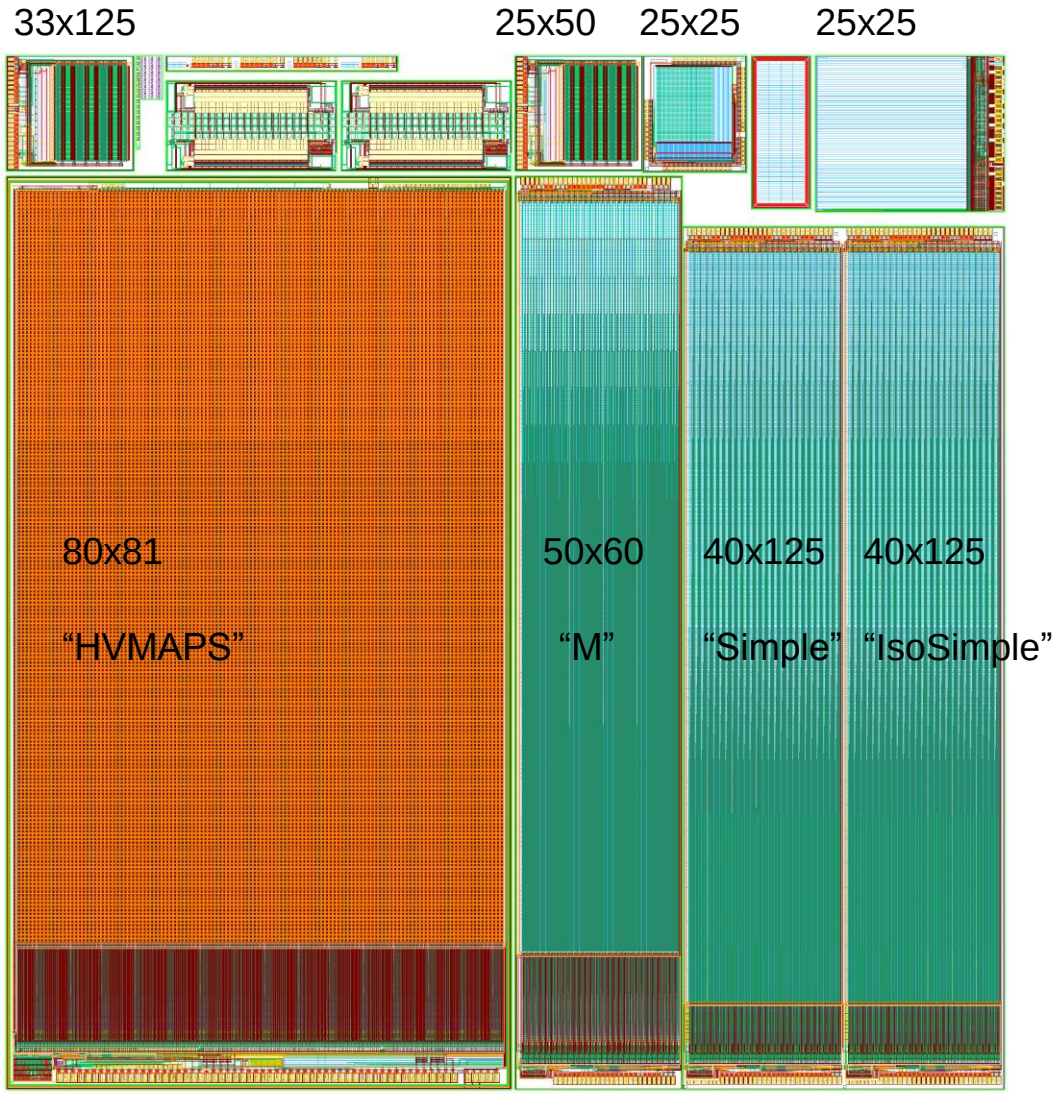
MuPix, ATLASPIX

- …


CCPD_1stGen
Belle II Switcher
CCPD_2ndGen
C3PD
Rad-hard MuPix
ATLASPix
Trigger readout
CCPD_2ndGen
Triggerless readout
SmartDio
SmallDio
PMOS
IsoPMOS
Trigger readout
Triggerless readout
WavePix
LFATLASPIX
MuPix, ATLASPIX

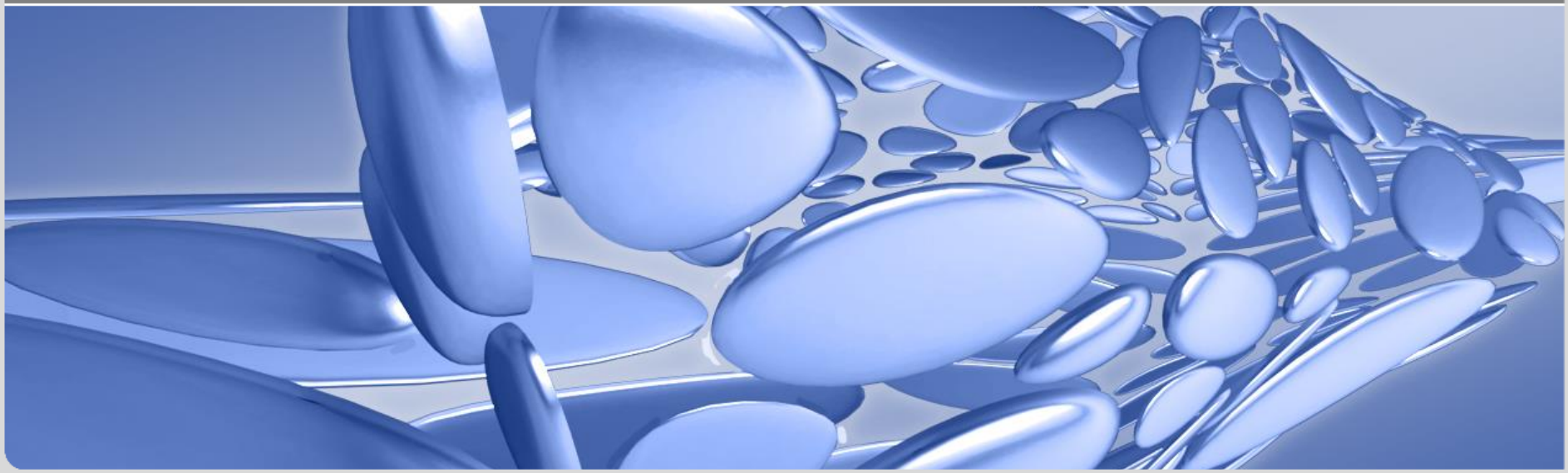


LFATLASPIX



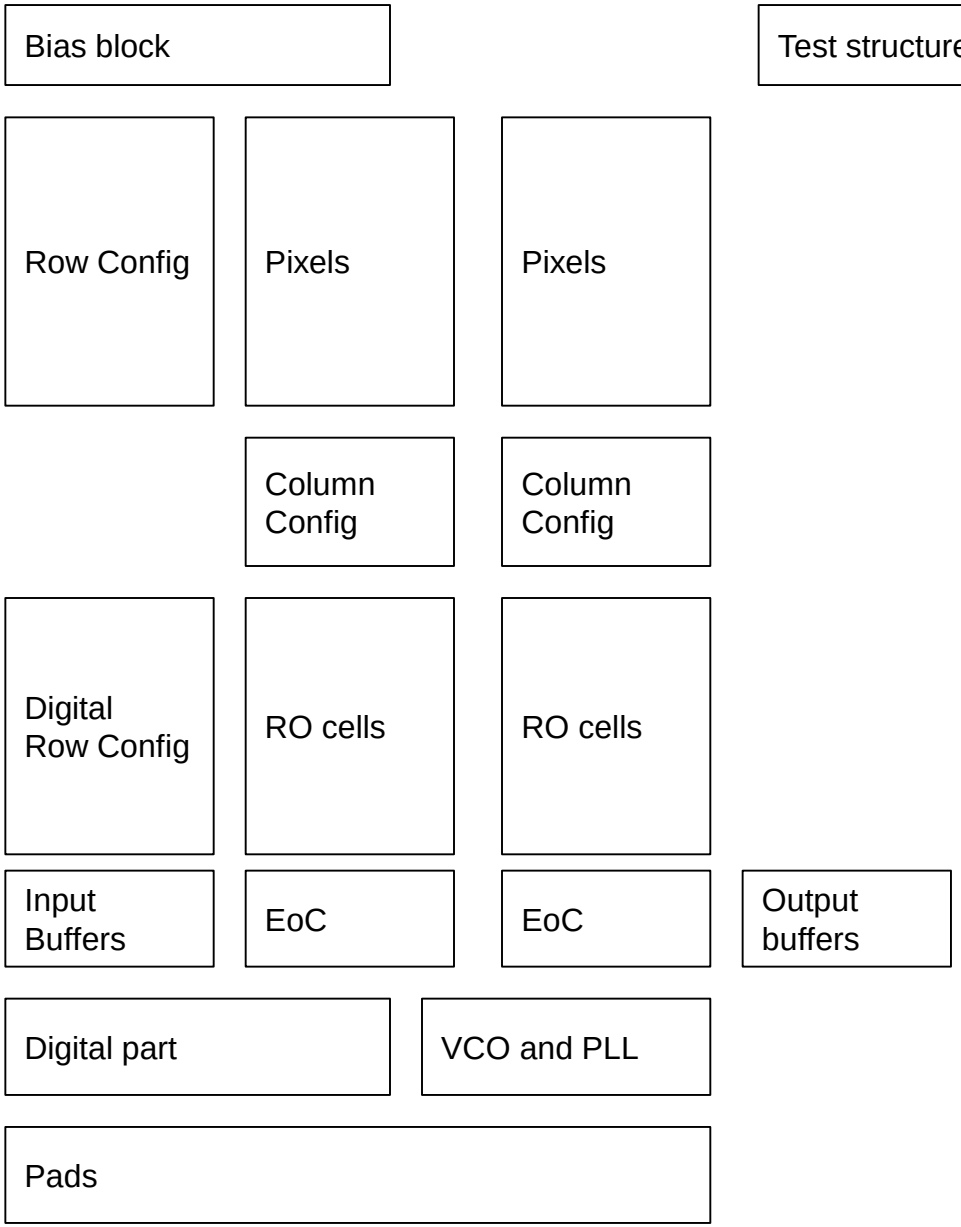
MuPix8, ATLASPIX

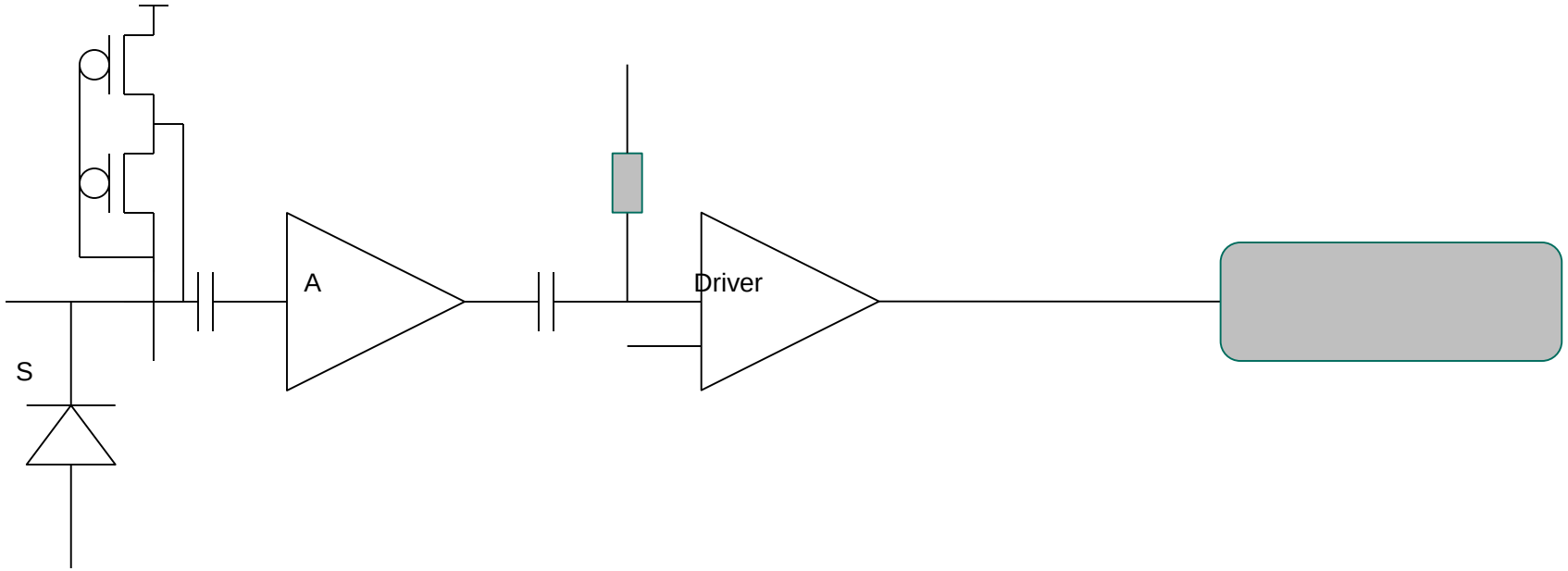
Radiation hard HV-MAPS – MuPix8



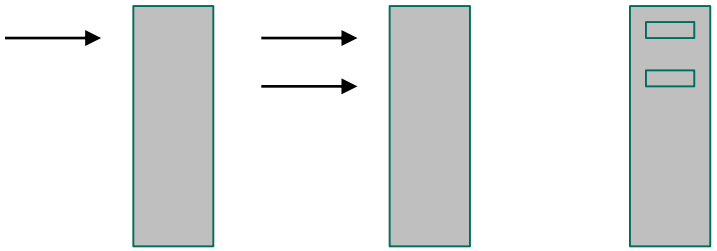
- Pixel Size: 80um x 81um
- Size of the matrix: 200 x 128 pixels -> about 1.6cm x 1cm
- Pixels contain only charge sensitive amplifier and output driver
- Hit information: x-address, y-address, 10-bit time stamp, 6-bit amplitude
- Amplitude measurement: ToT or Ramp ADC programmable
- Input Clock 6.25ns
- Output data rate: 3 x 1.6Gbit/s or 3 hits / 20ns
- Time resolution up to 6.25ns
- Nominal power consumption: pixel matrix: 300mW
- Data interface: Ck, Reset, 3 x data output
- Slow control: Shift register
- Voltages: 0, 1.8V, 1.1V
- Pad pitch 150um

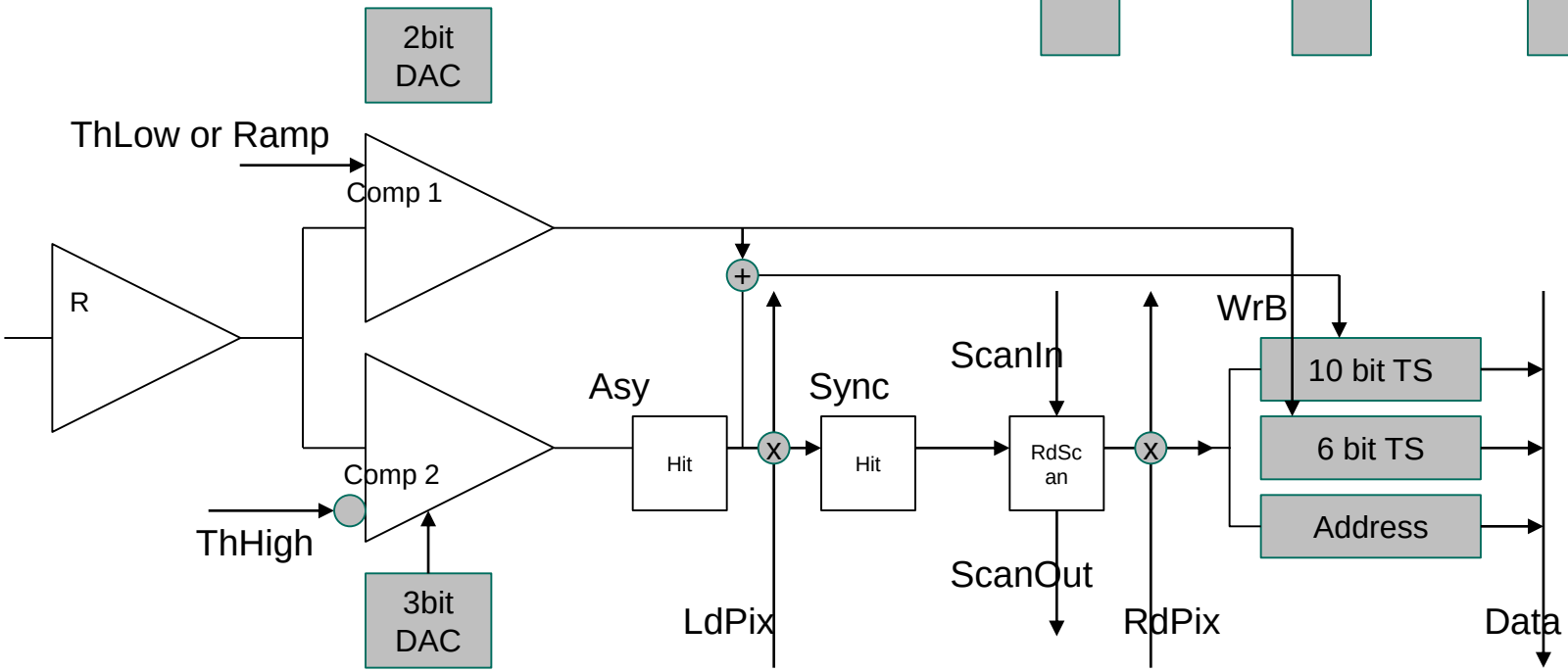
- …


Bias block
Test structures
Row Config
Pixels
Pixels
Column Config
Column Config
Digital Row Config
RO cells
RO cells
Input Buffers
EoC
EoC
Output buffers
Digital part
VCO and PLL
Pads


A
Driver
S

- Working modi:
- Time over threshold
- Ramp ADC
- Two thresholds





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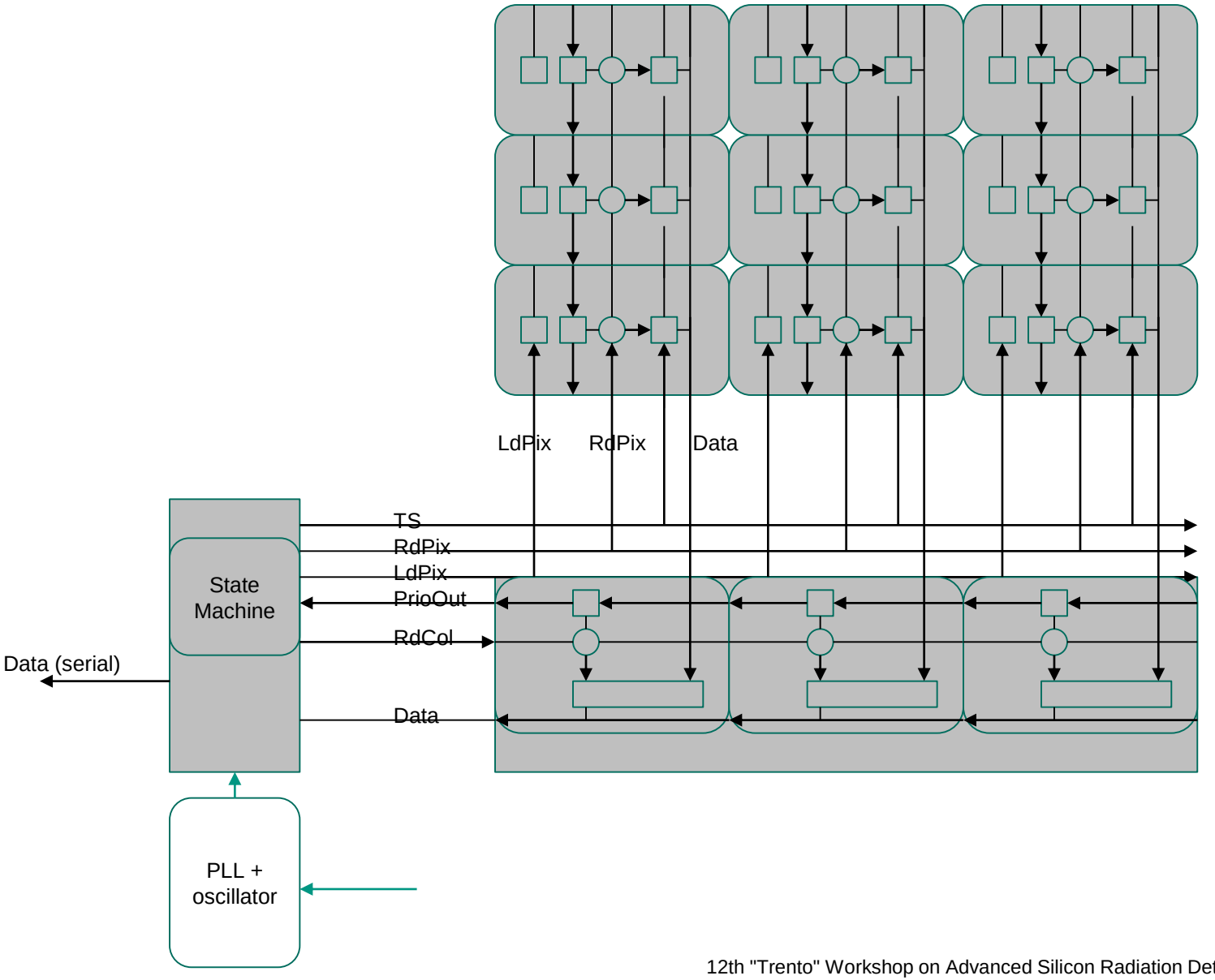
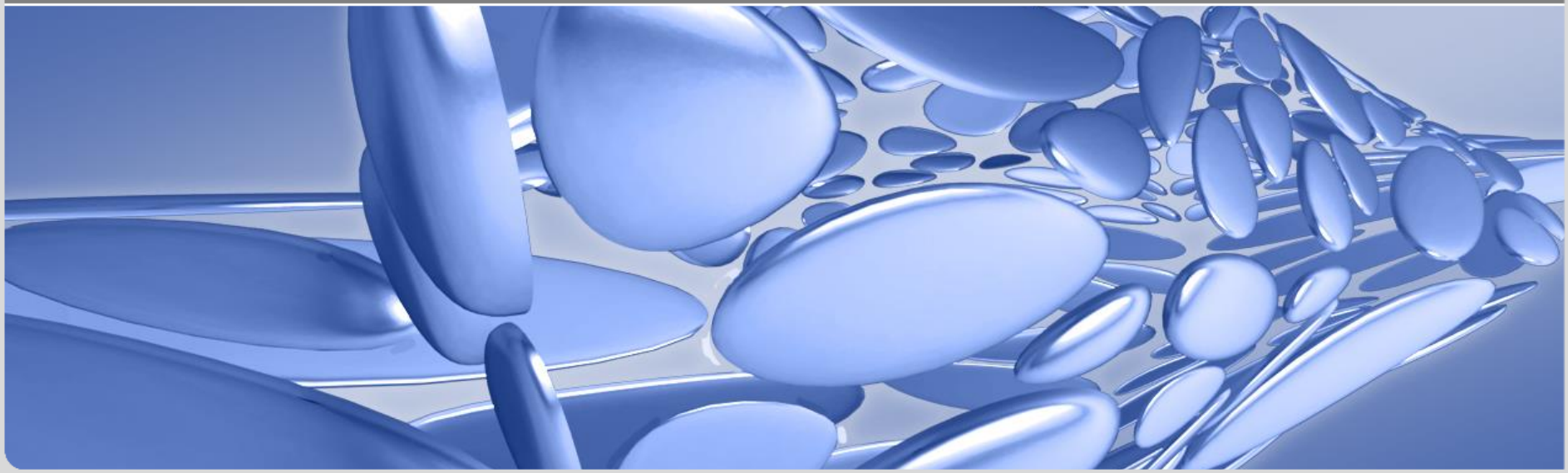
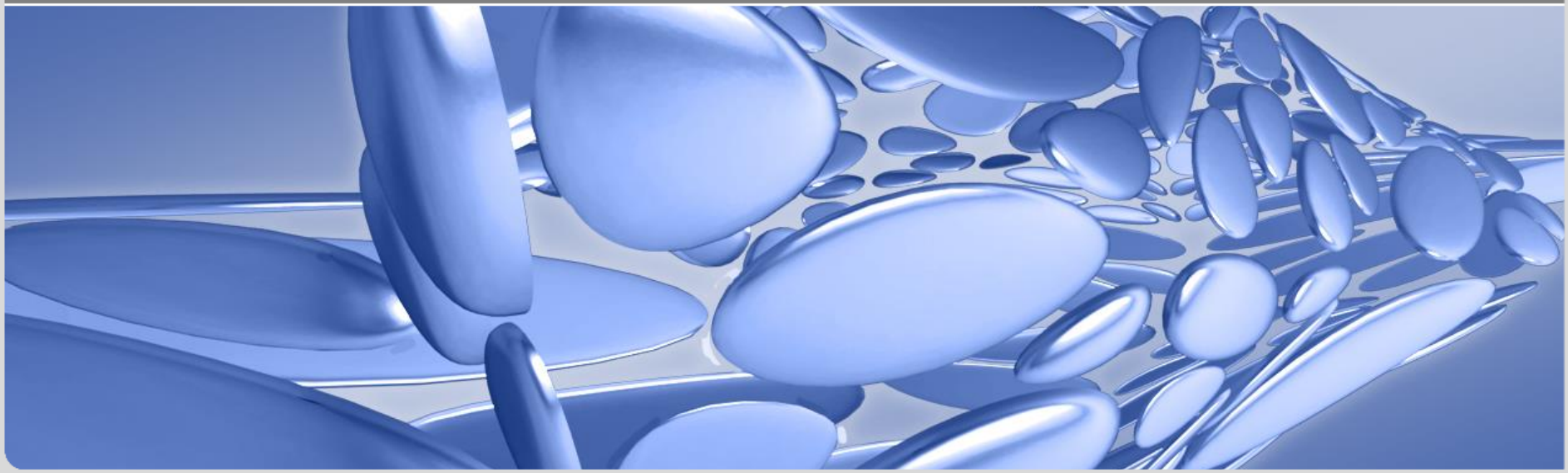

LdPix
RdPix
Data
TS
RdPix
LdPix
PrioOut
RdCol
Data
State Machine
Data (serial)
PLL + oscillator

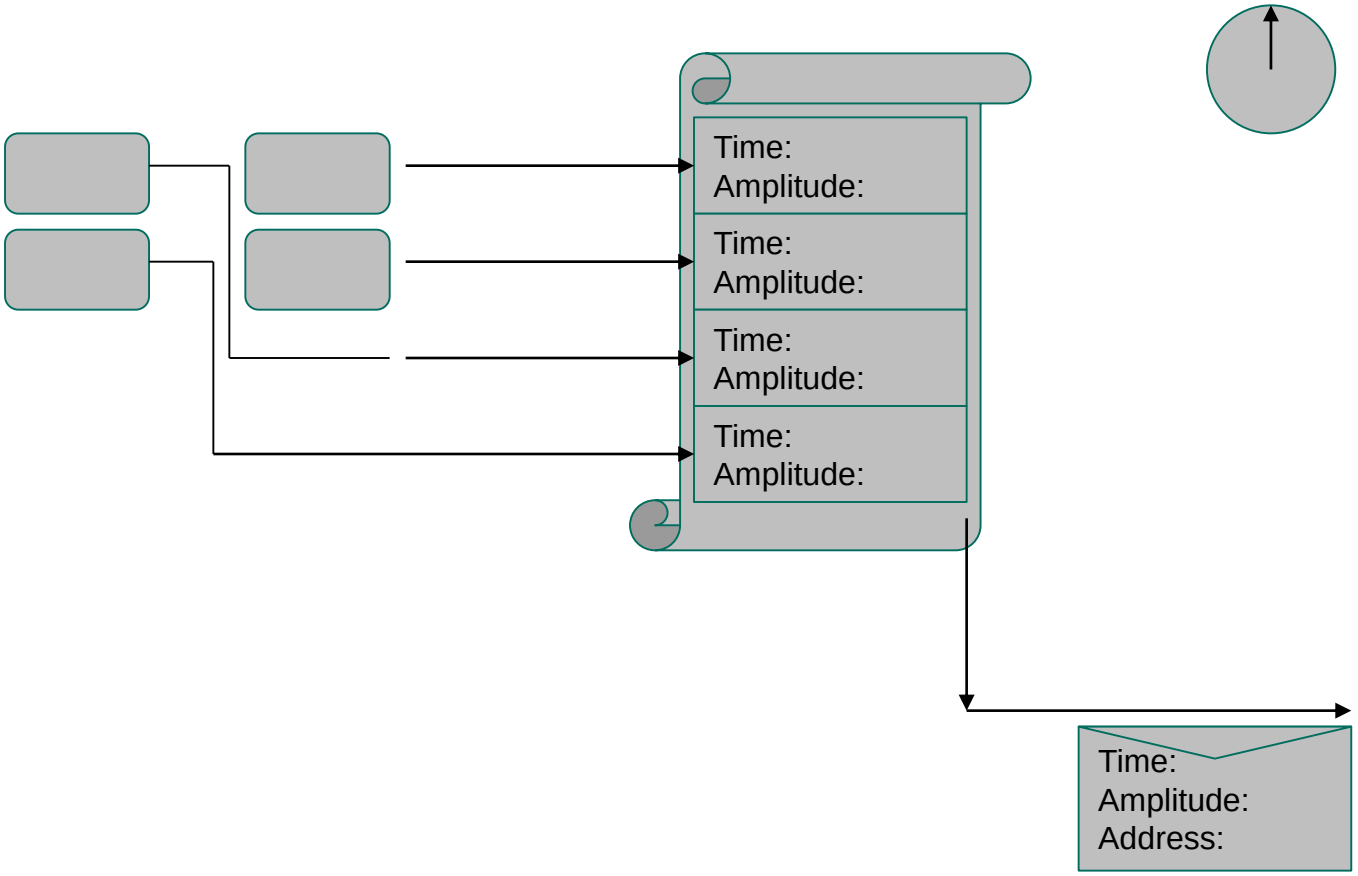
Advanced features



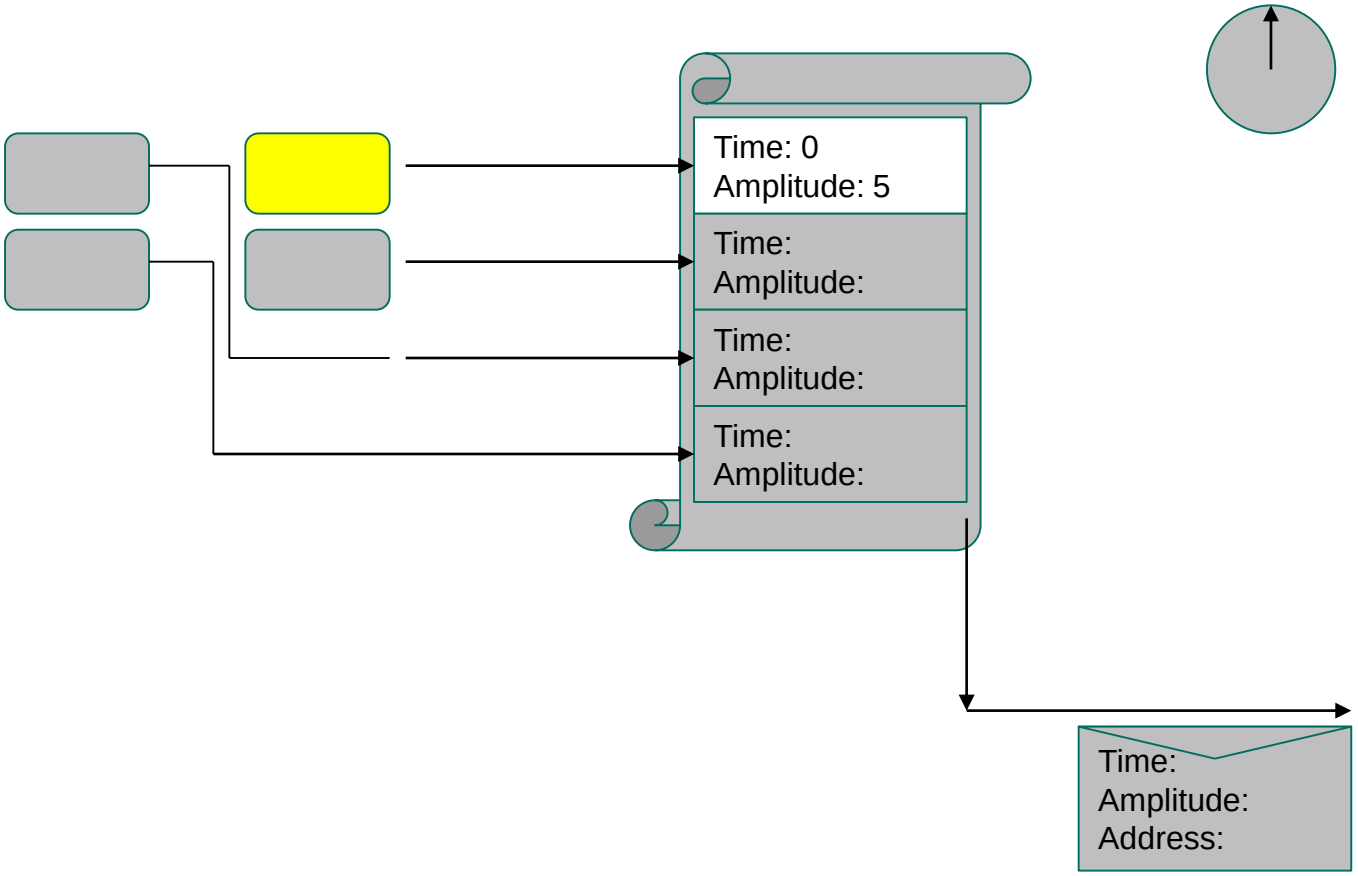
Readout types



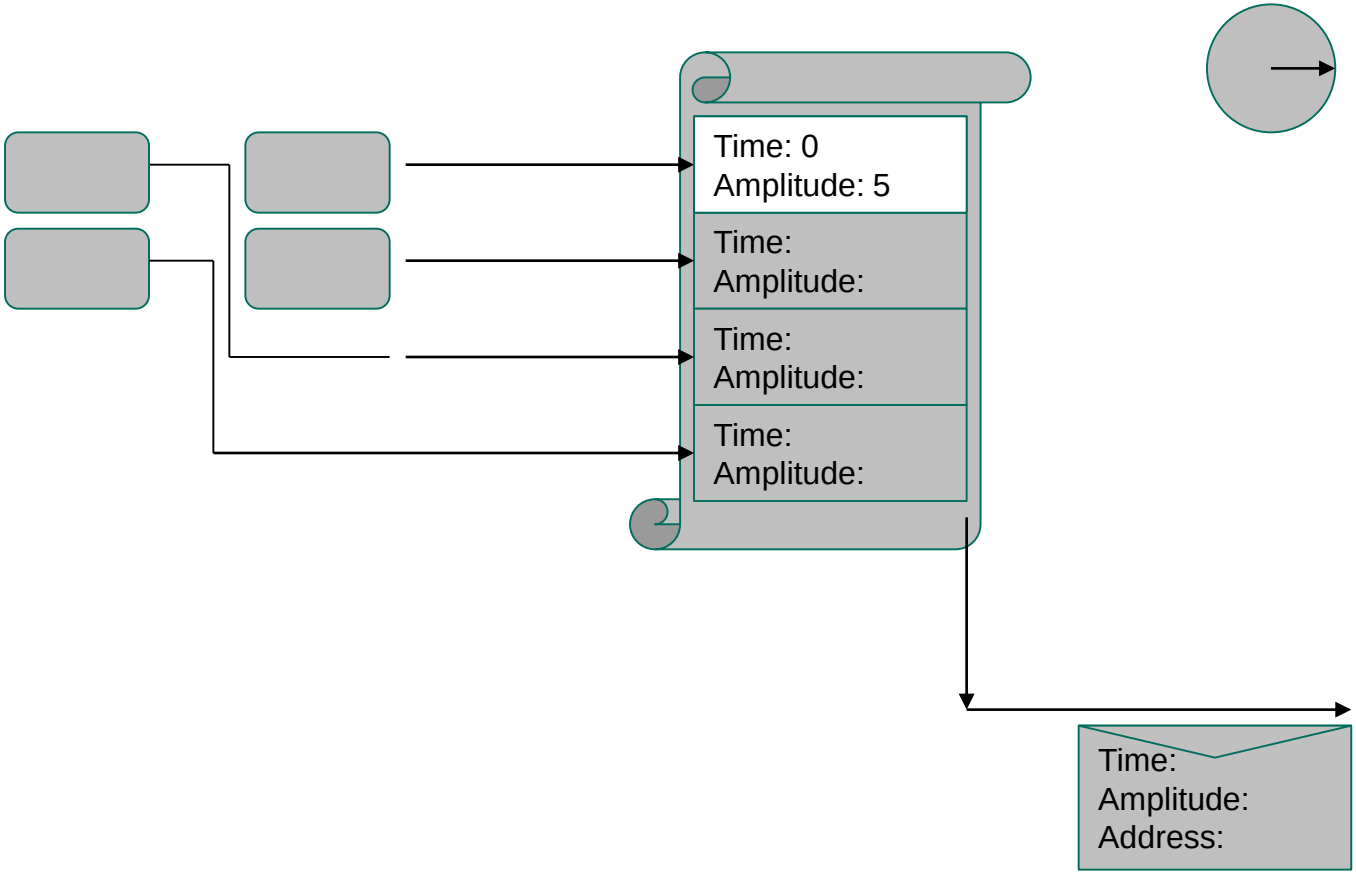
- Hit driven, trigerless, readout (MuPix8, Simple ATLASPix)



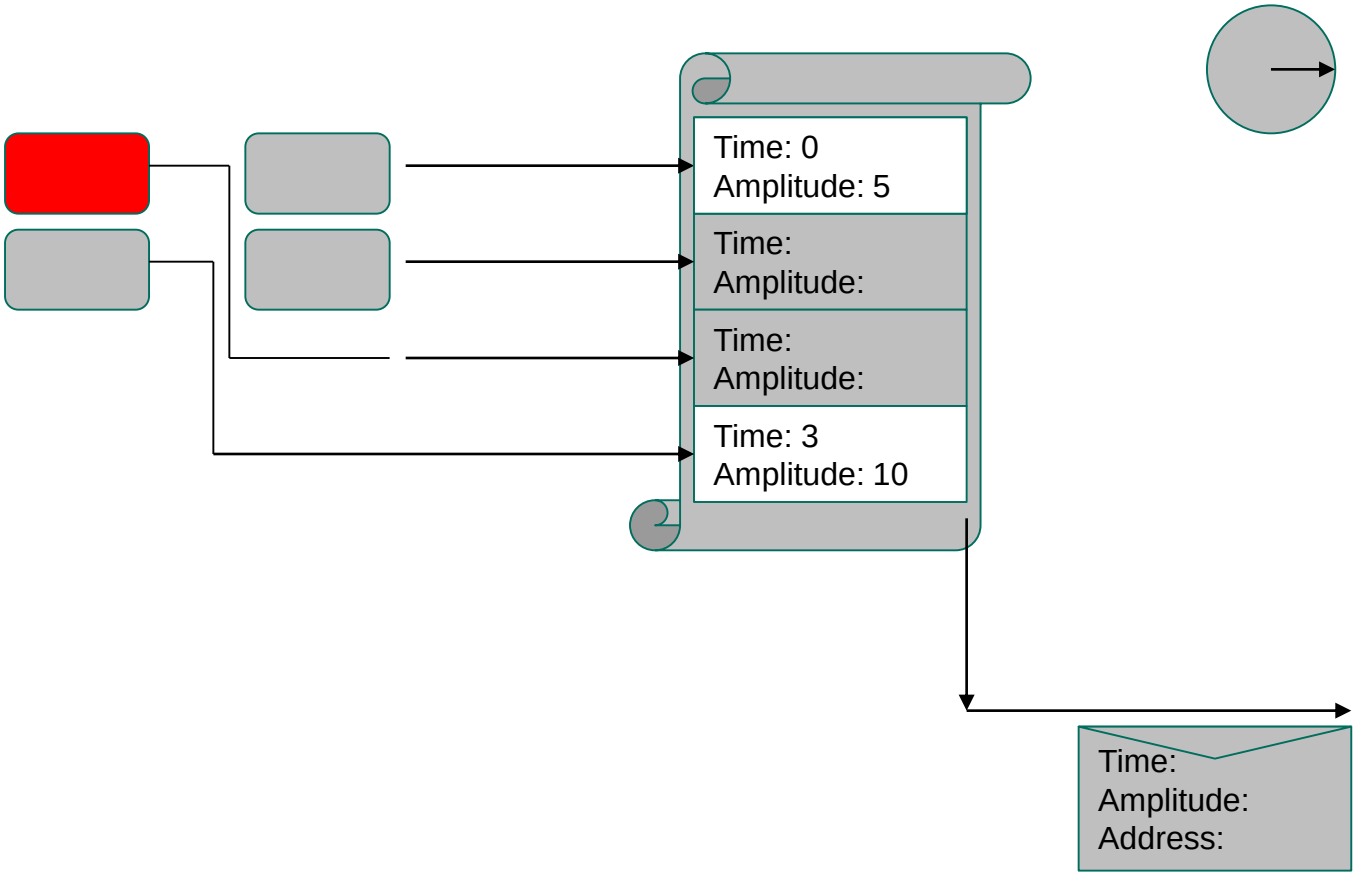
- Hit driven, trigerless, readout



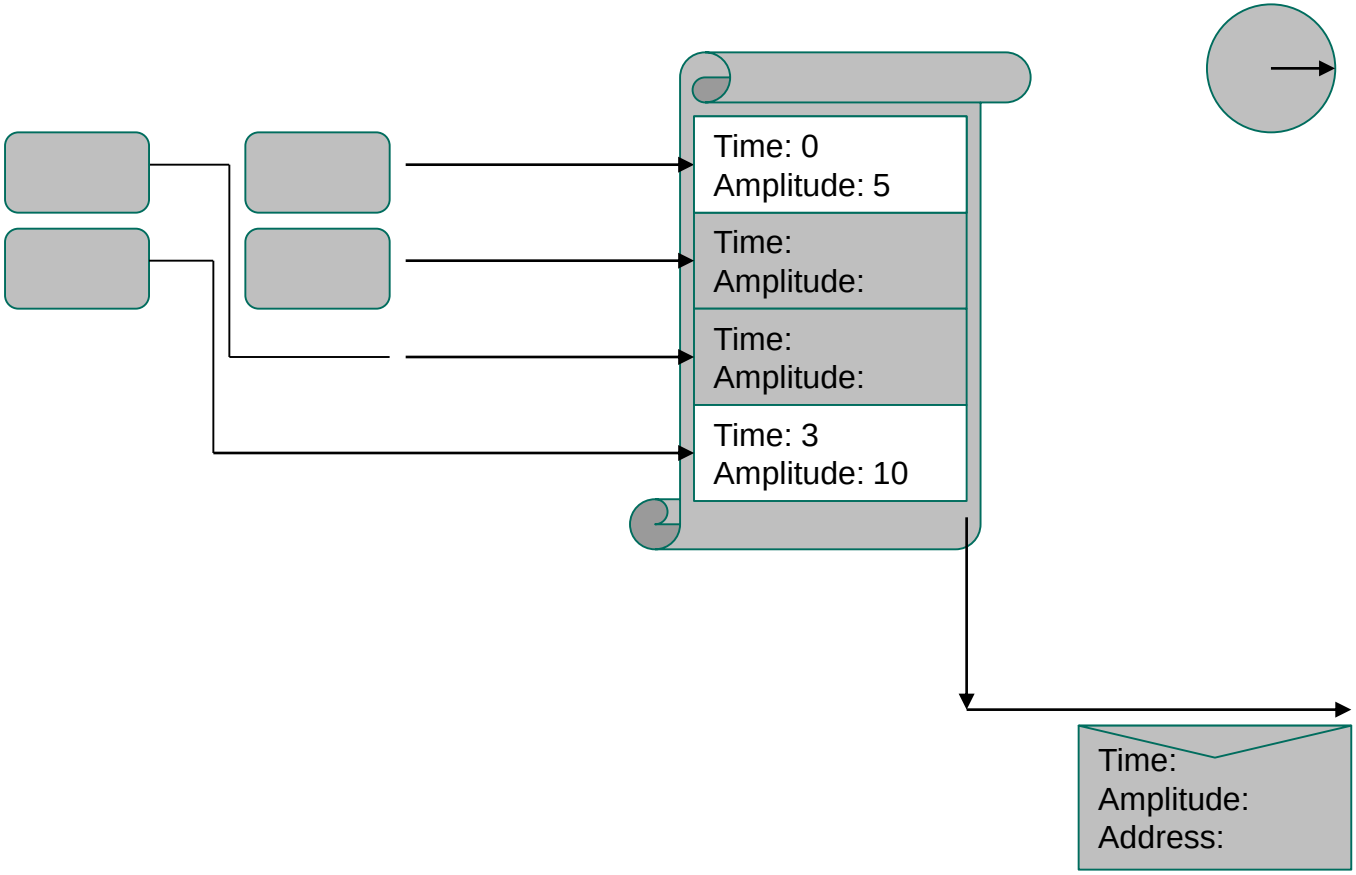
- Hit driven, trigerless, readout



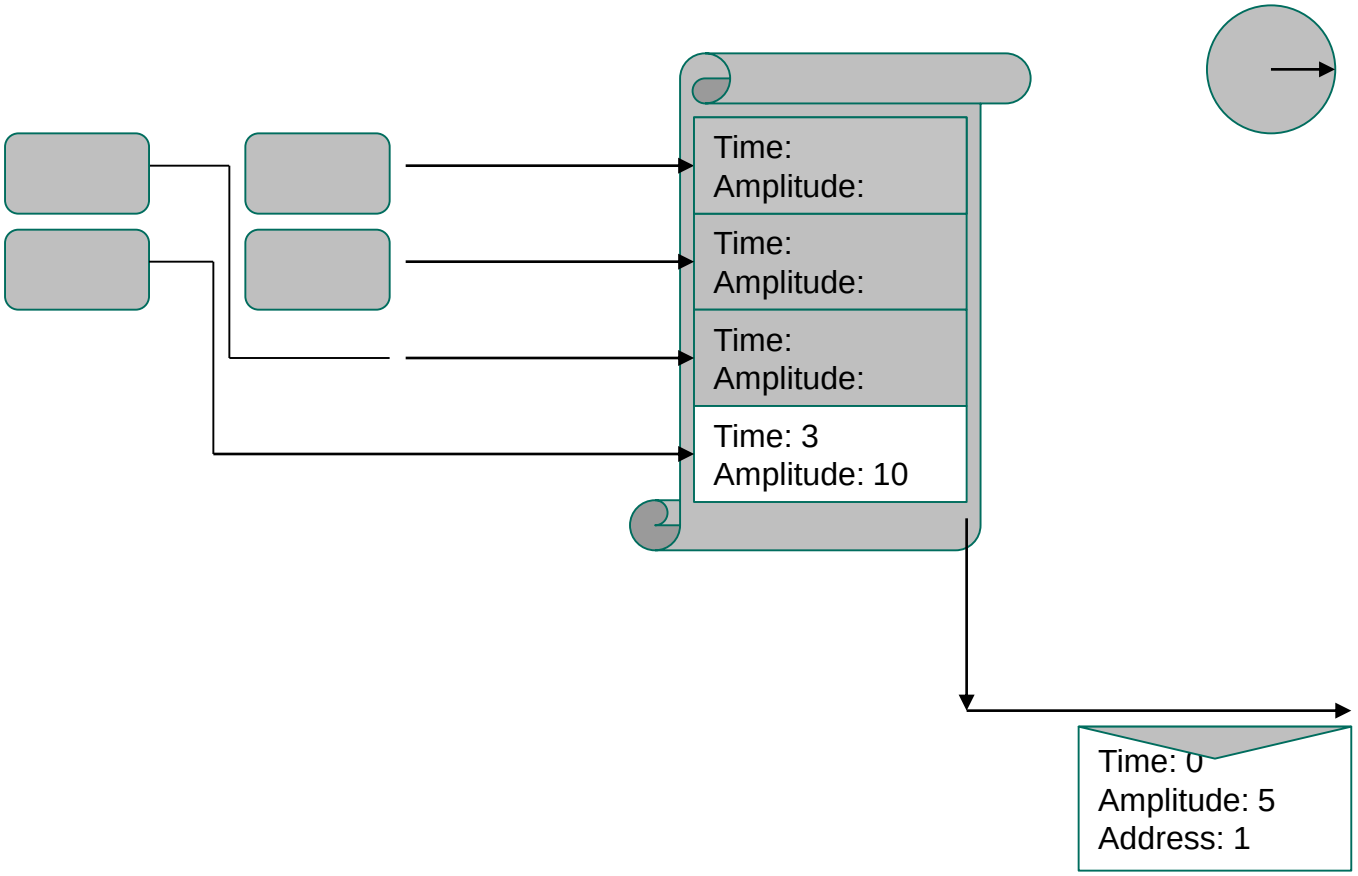
- Hit driven, trigerless, readout



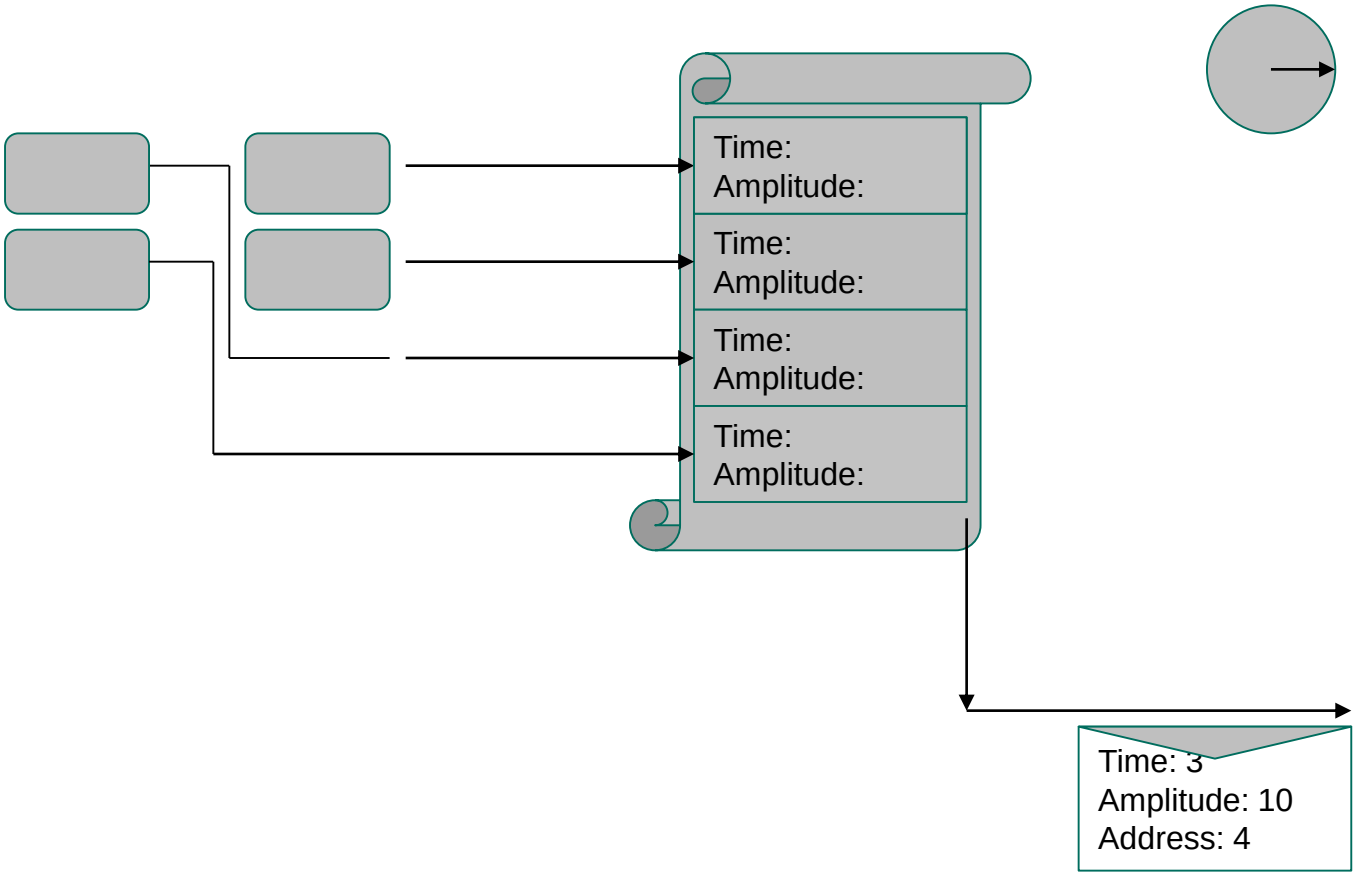
- Hit driven, trigerless, readout



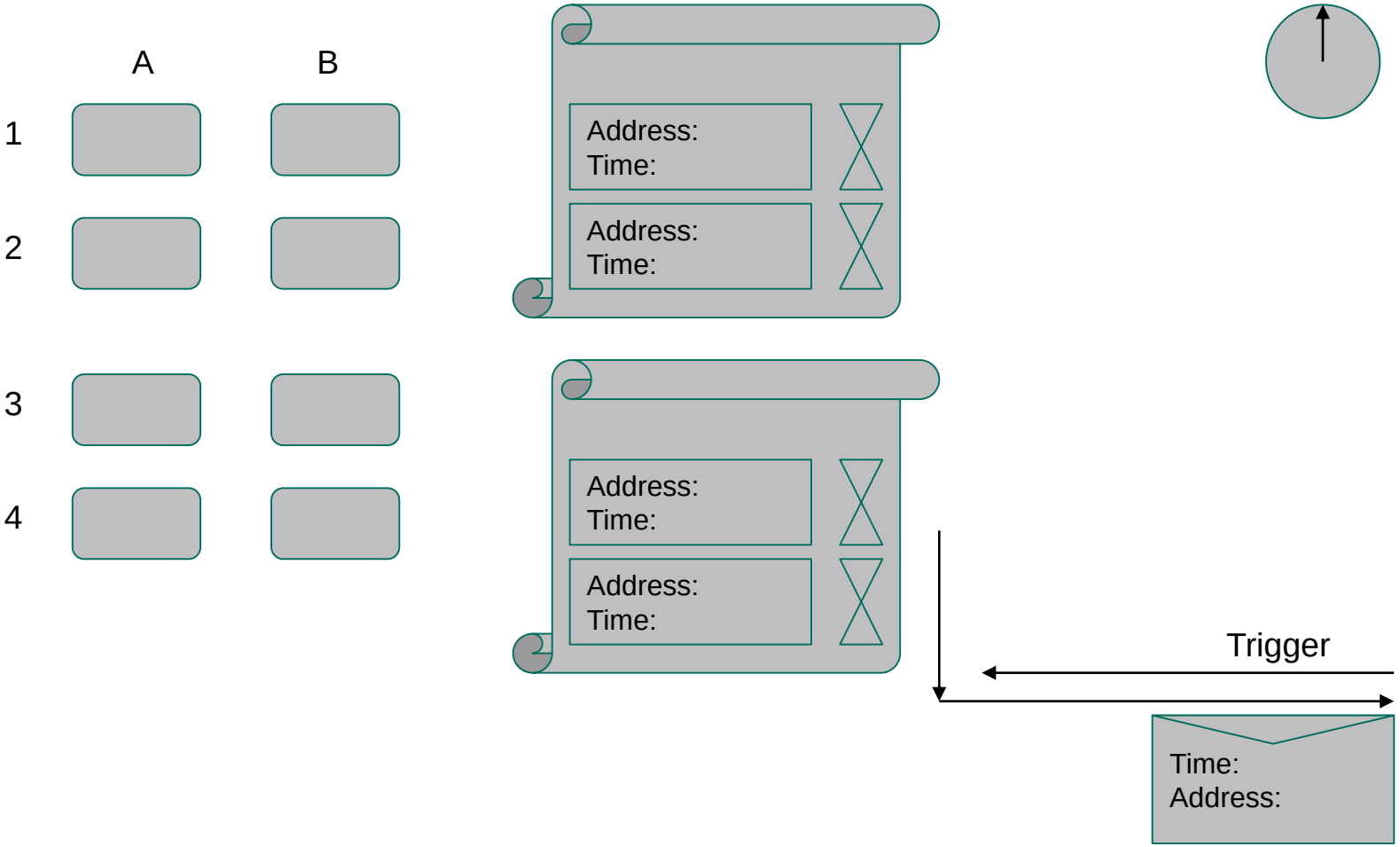
- Hit driven, trigerless, readout



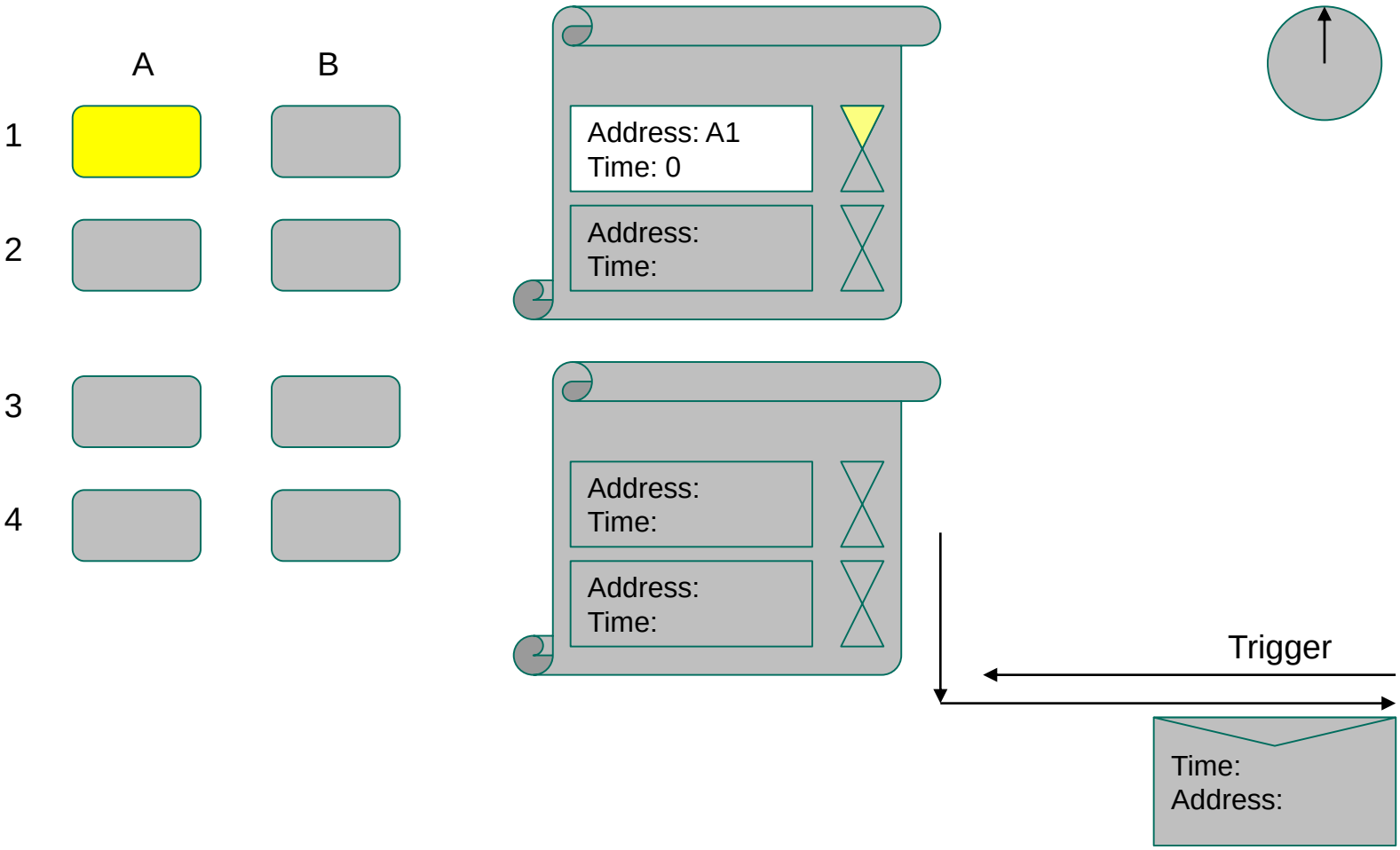
- Hit driven, trigerless, readout



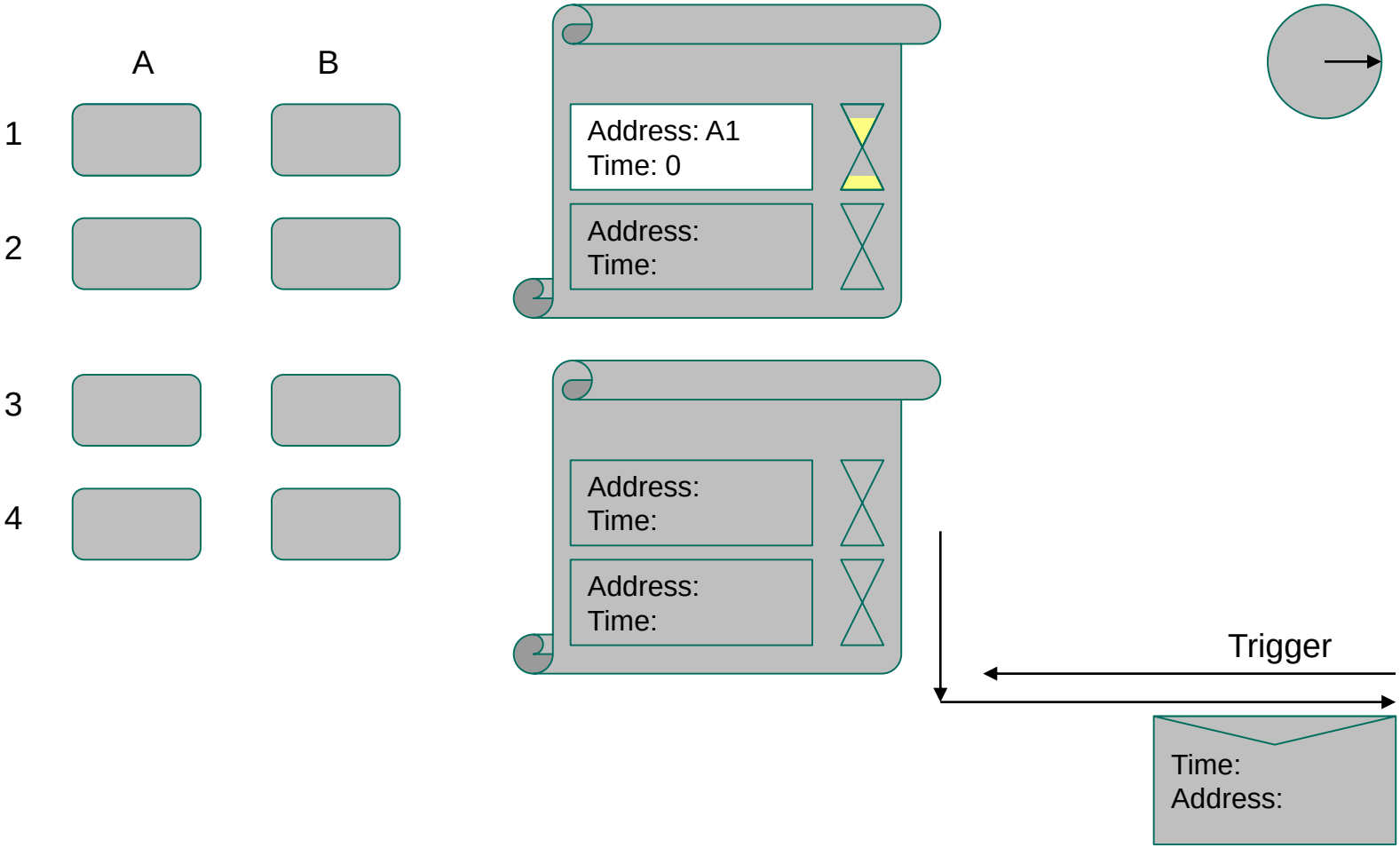
- Triggered readout (M ALTASPix)



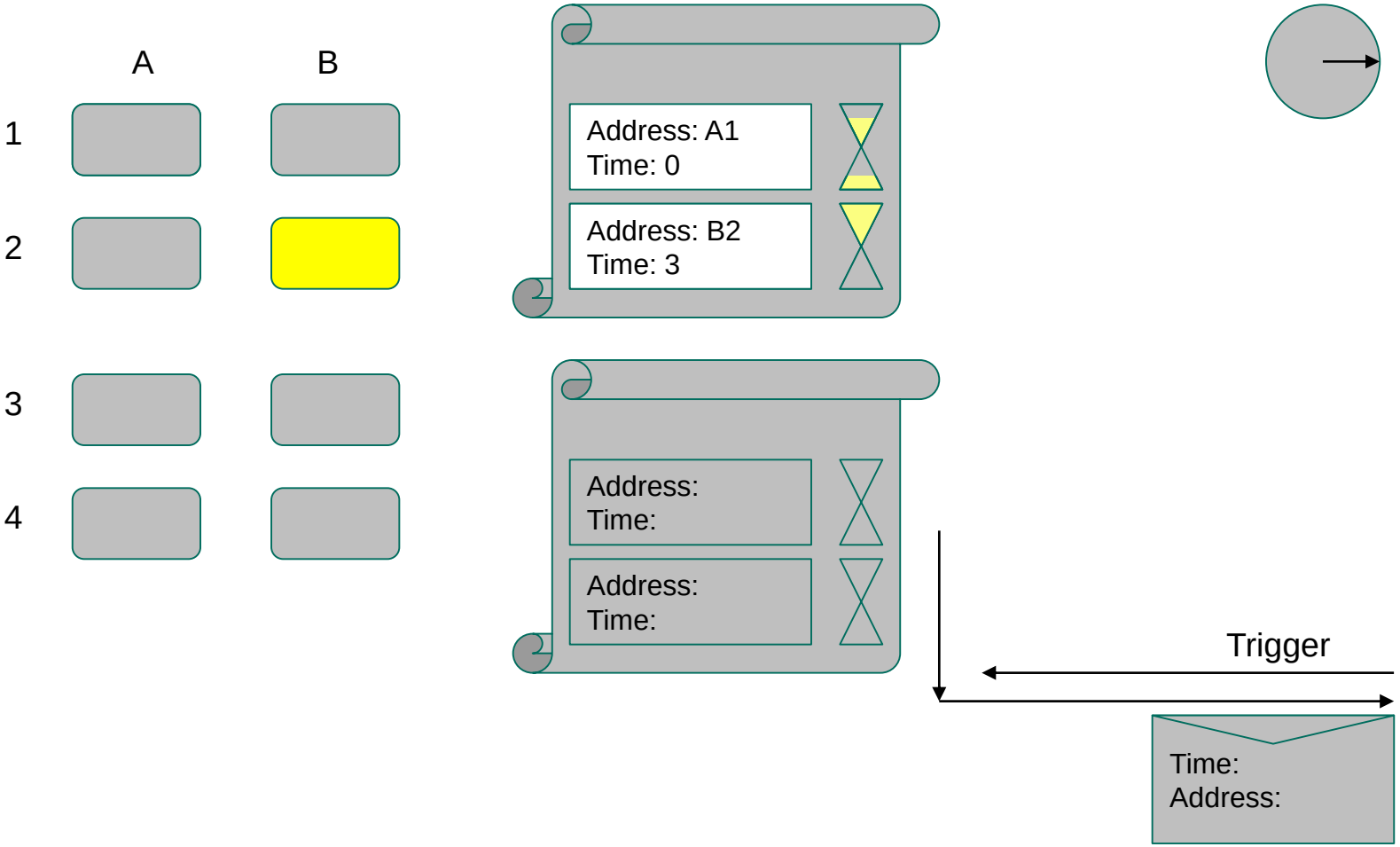
- Triggered readout



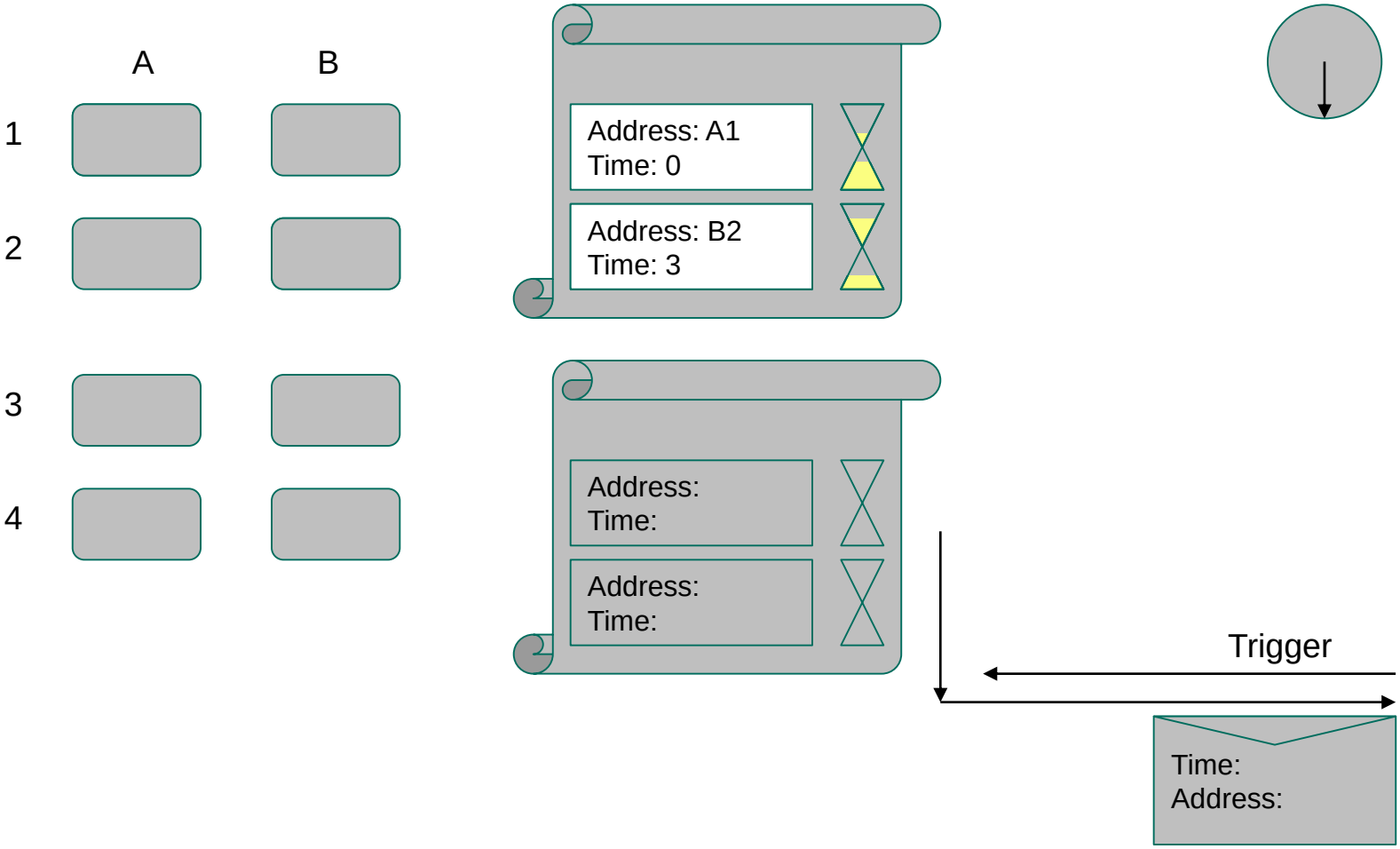
- Triggered readout



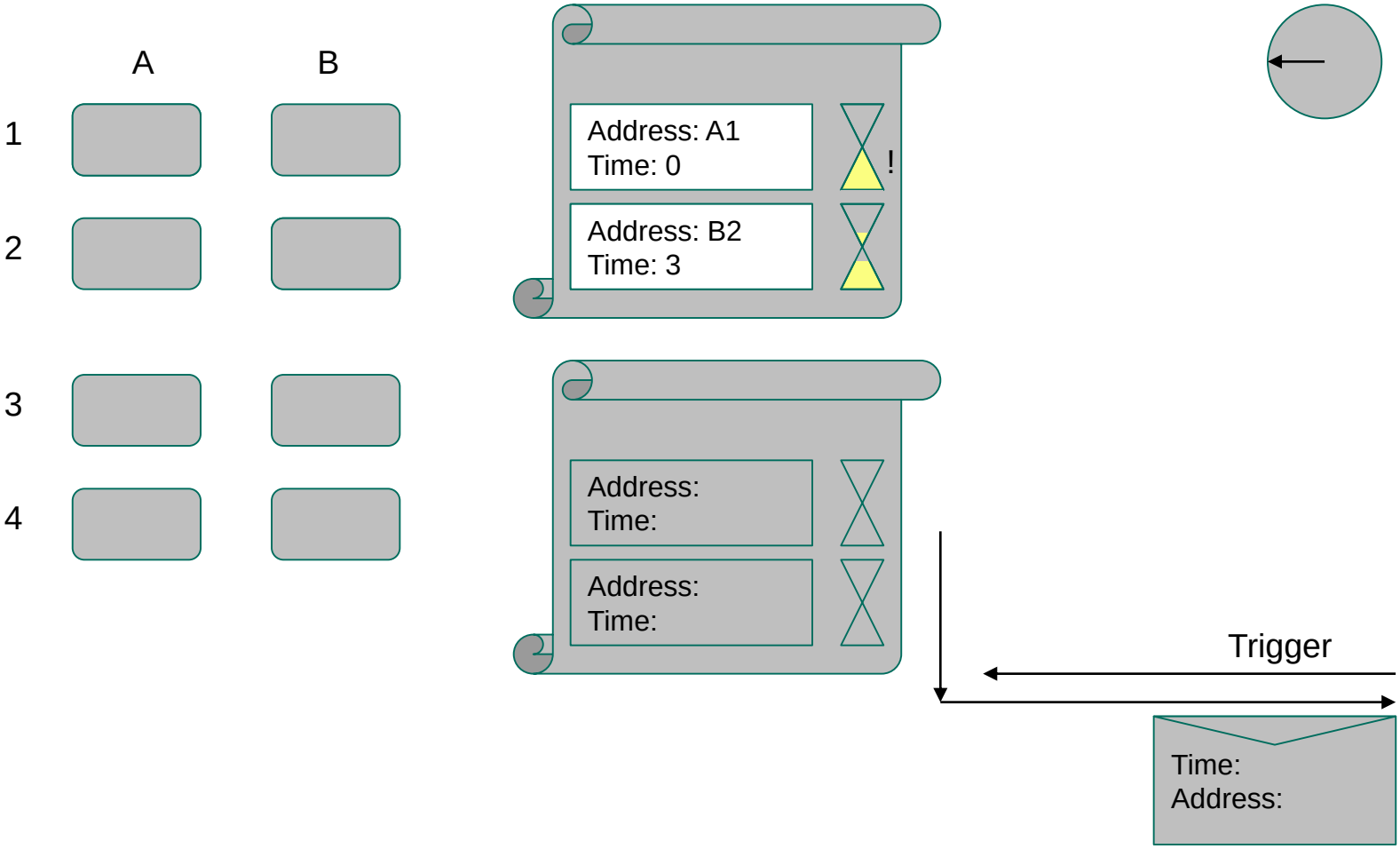
- Triggered readout



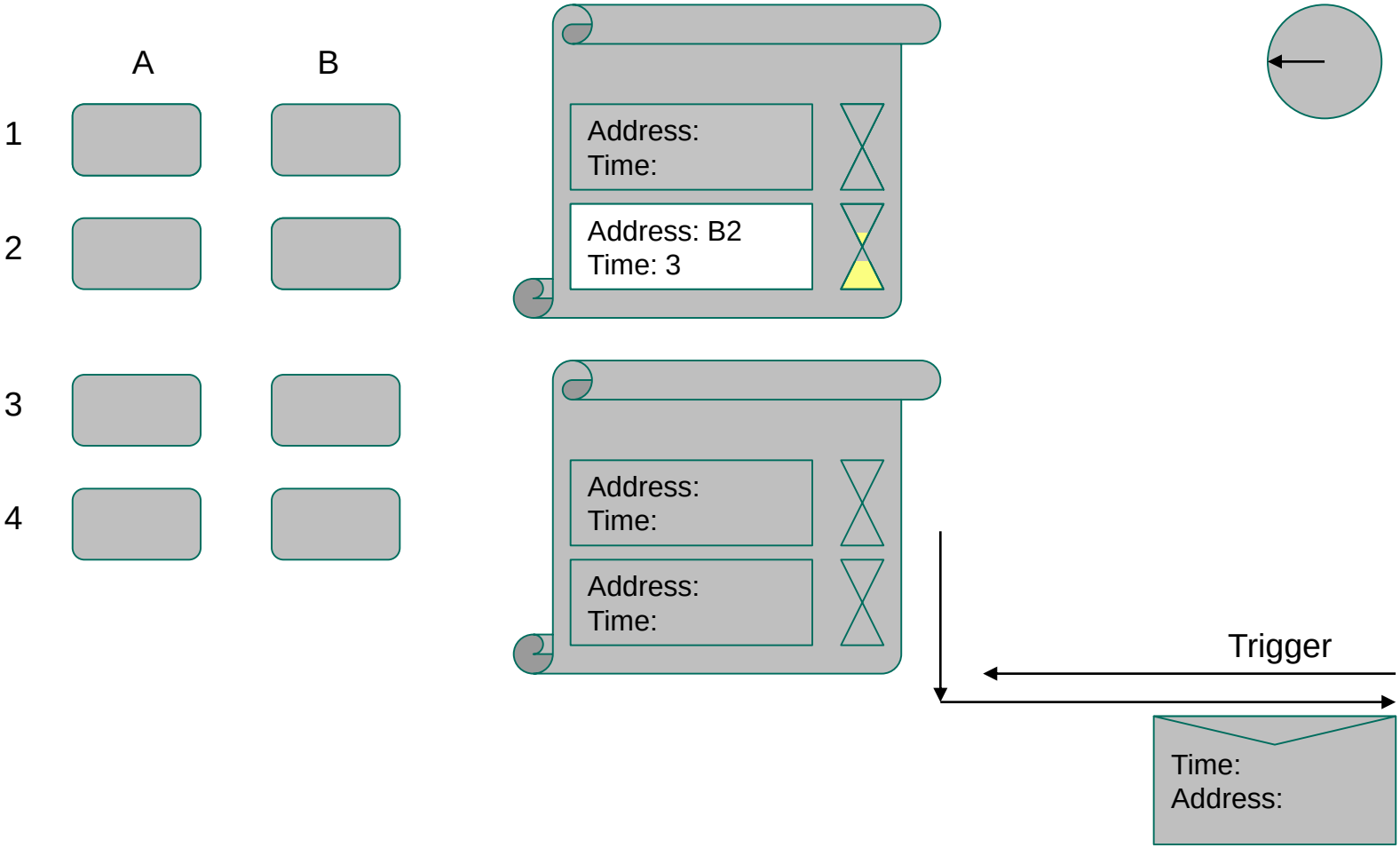
- Triggered readout



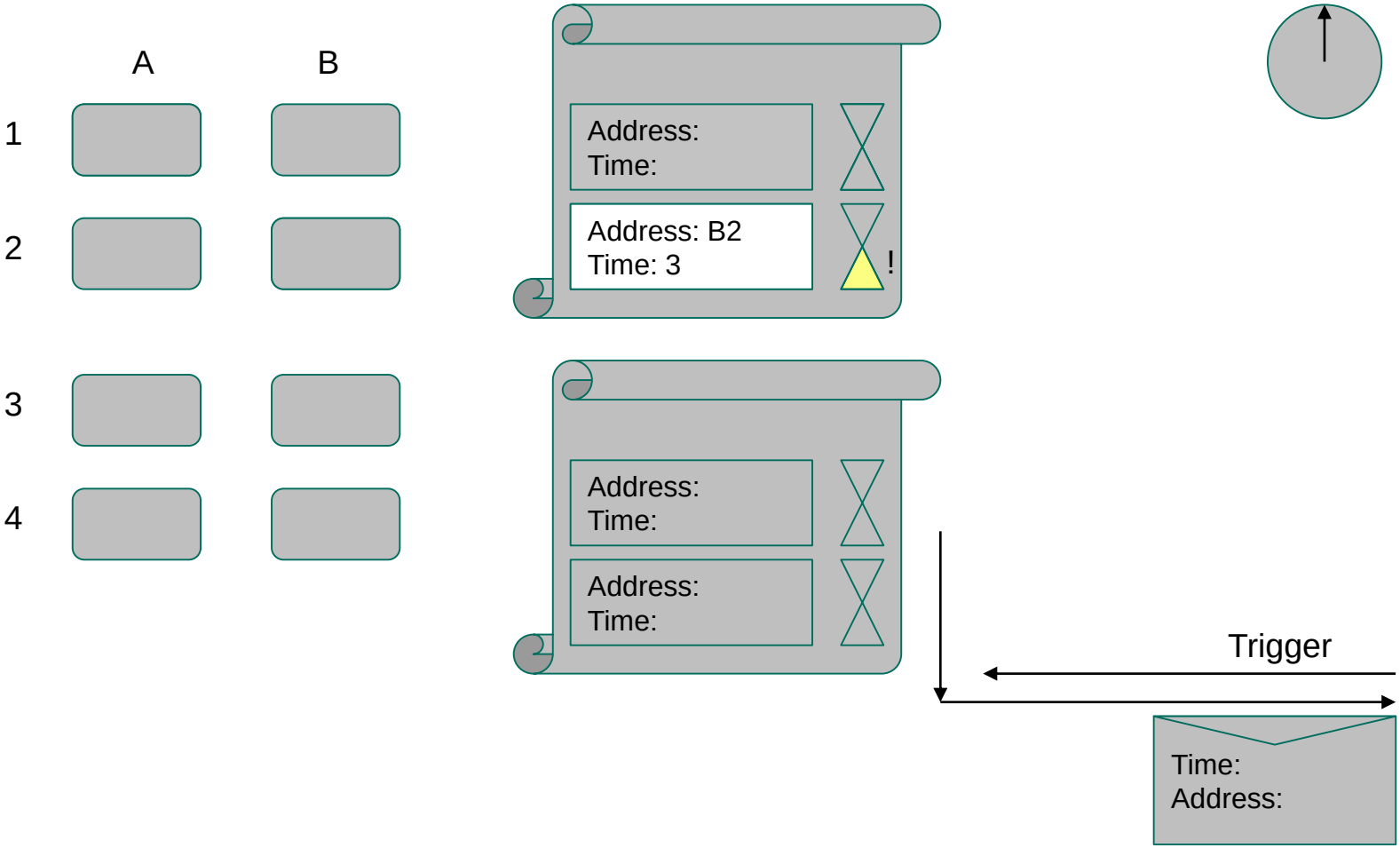
- Triggered readout



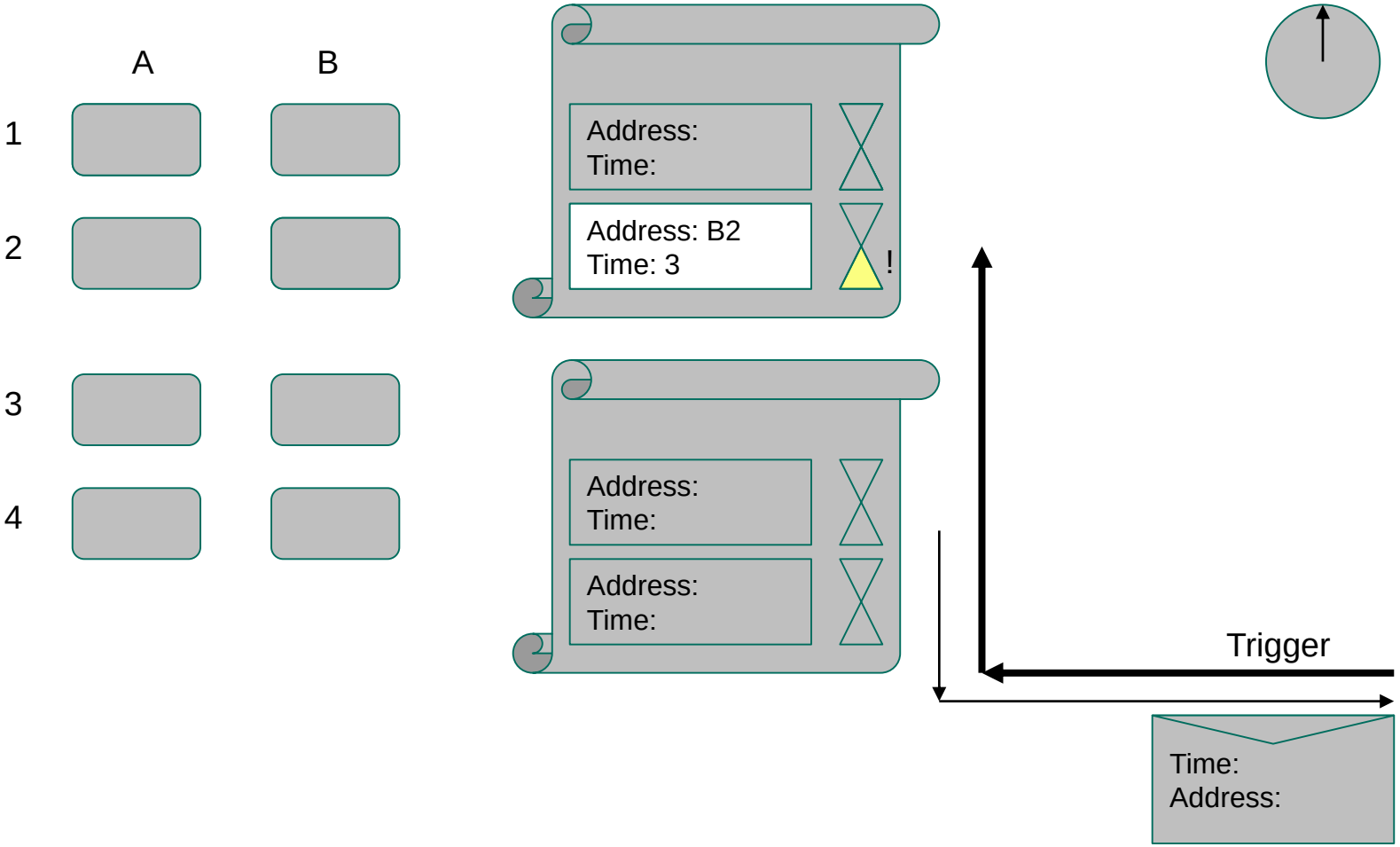
- Triggered readout



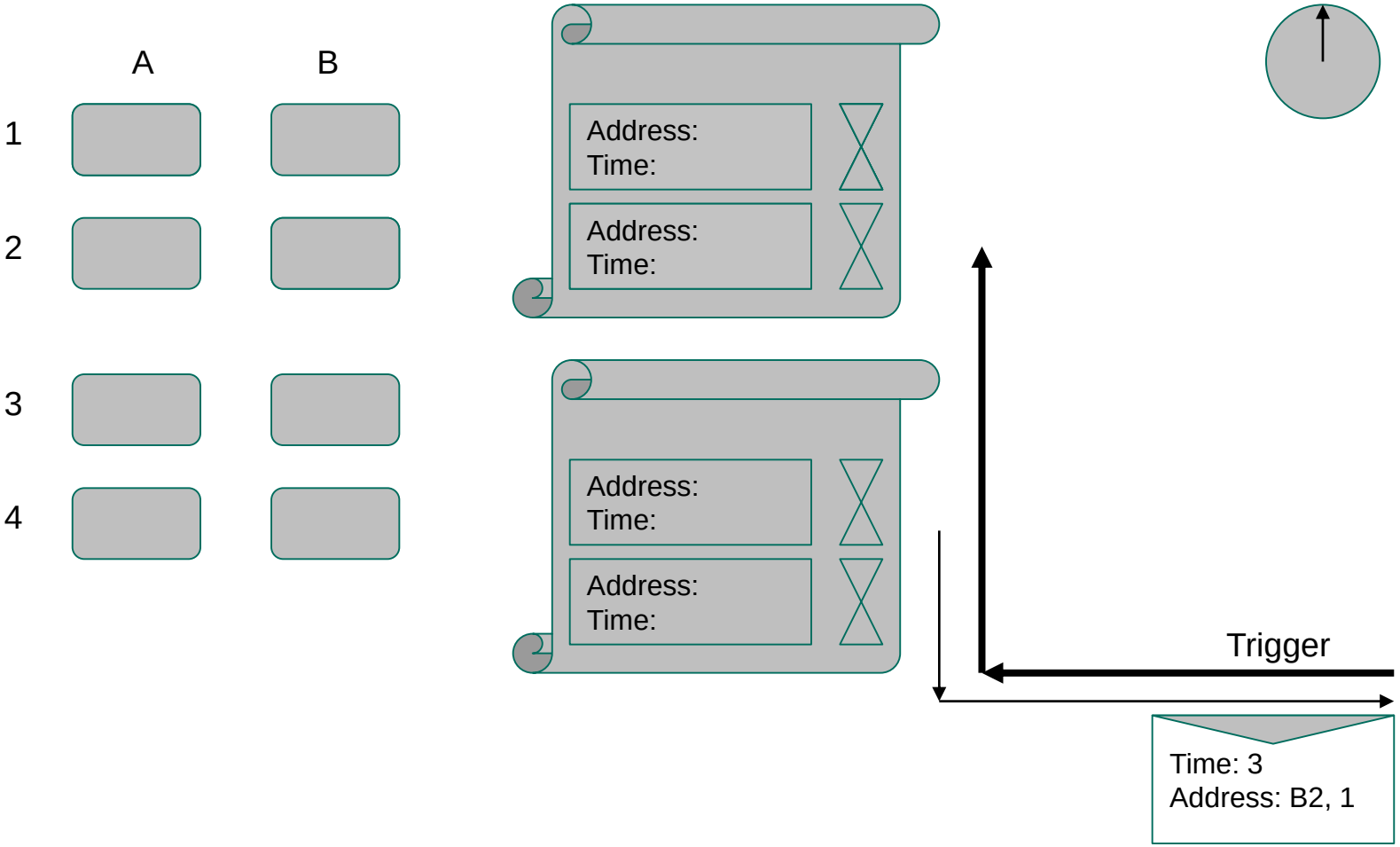
- Triggered readout



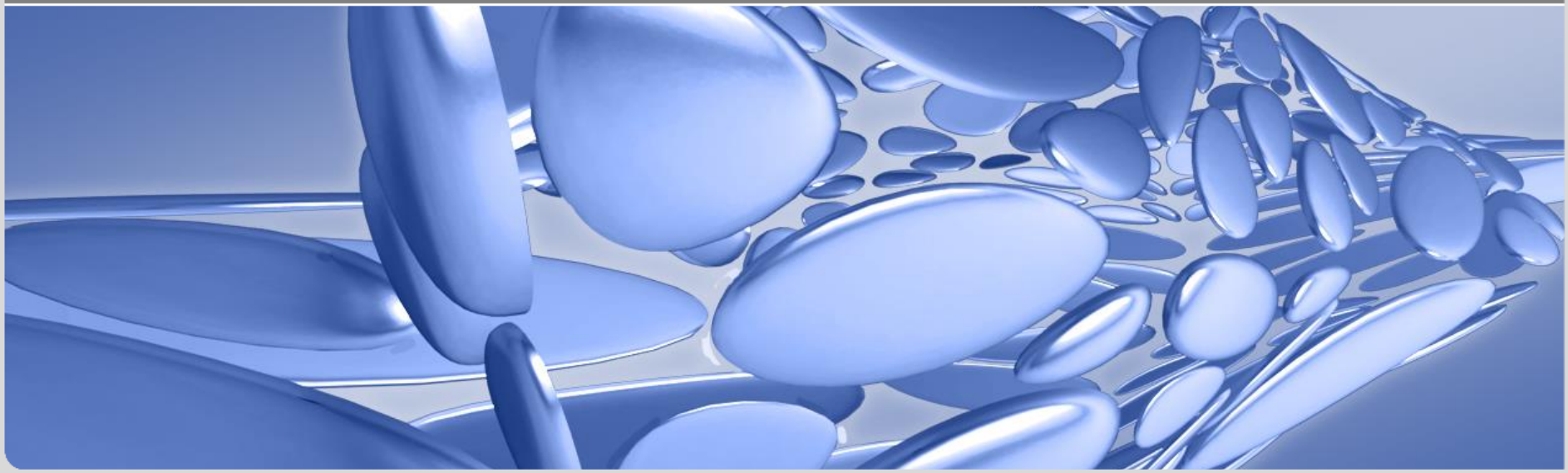
- Triggered readout



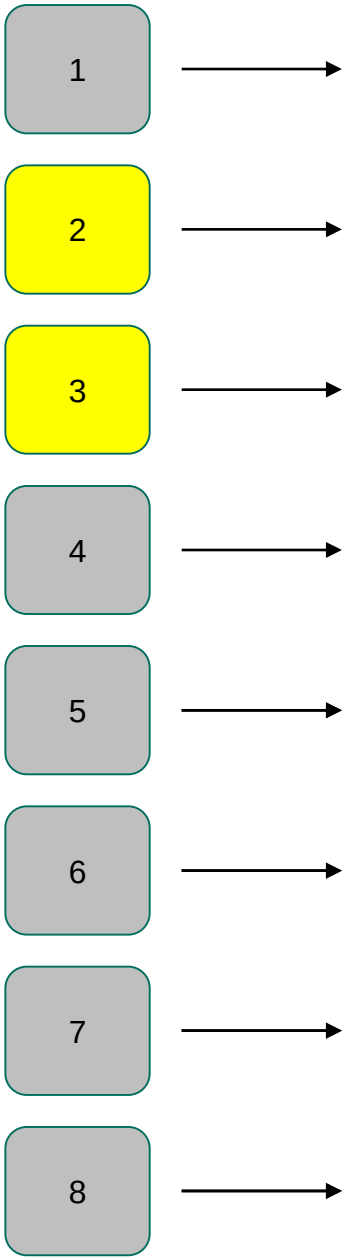
- Triggered readout

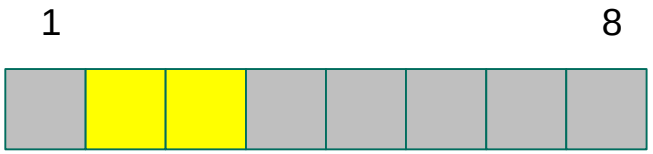


Address compression for triggered readout

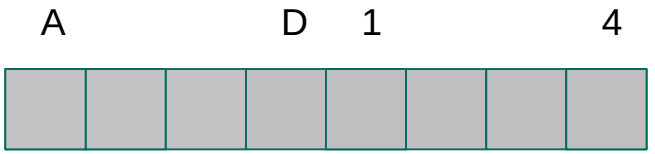


- 1-1 Address scheme
- MuPix, Simple ATLASPix



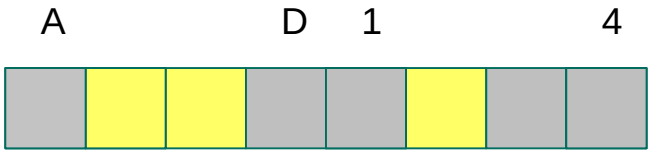


- Strip-Like scheme



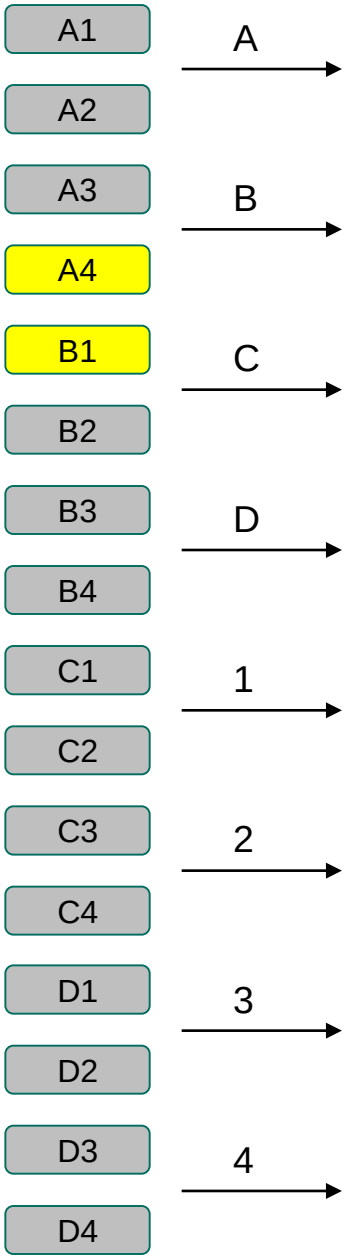
A1	B1	C1	D1
A2	B2	C2	D2
A3	B3	C3	D3
A4	B4	D4	E4

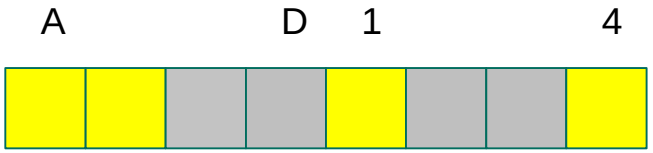
- Chess-like scheme



A1	B1	C1	D1
A2	B2	C2	D2
A3	B3	C3	D3
A4	B4	D4	E4

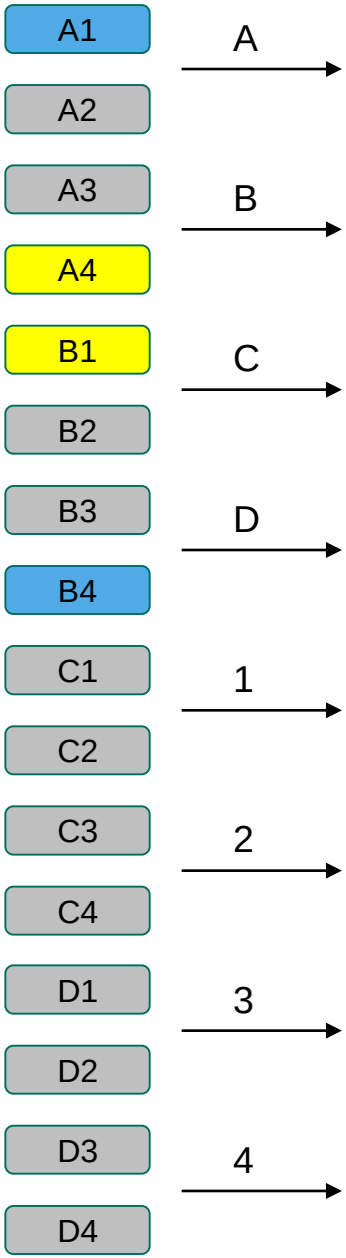
- Chess-like scheme (linear)
- M ATLASPix

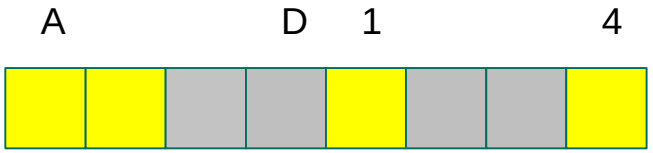




Two possibilities: A4, B1 and

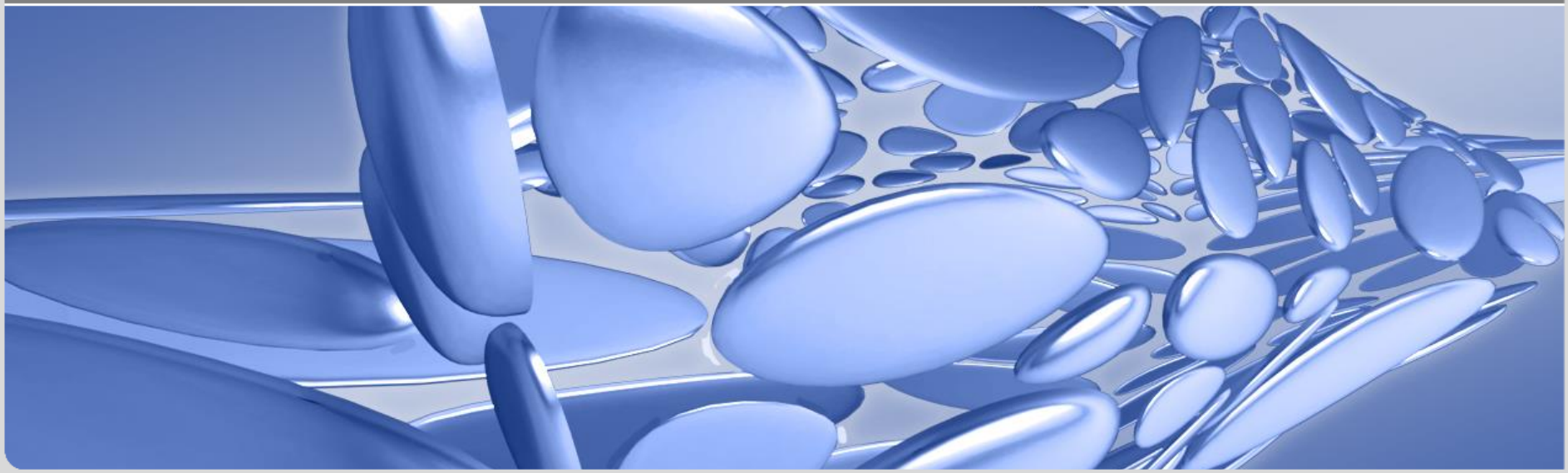
- Chess-like scheme (linear)

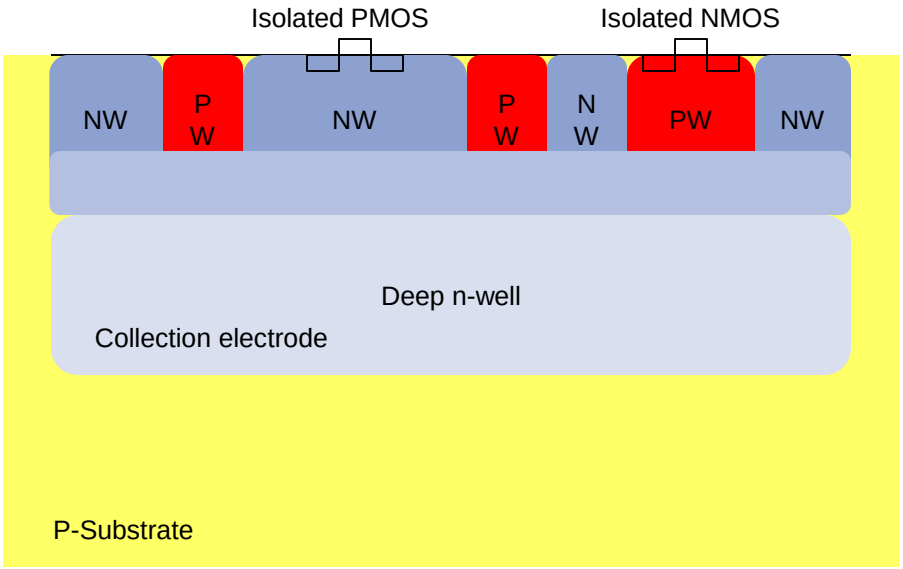




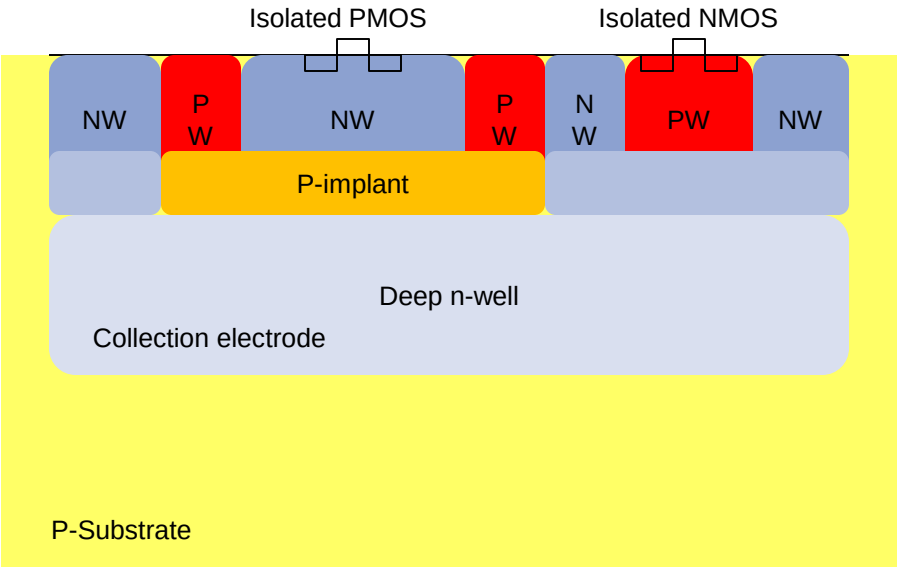
Two possibilities: A4, B1 and A1, B4
A1, B4 is less probable

Pixel forms

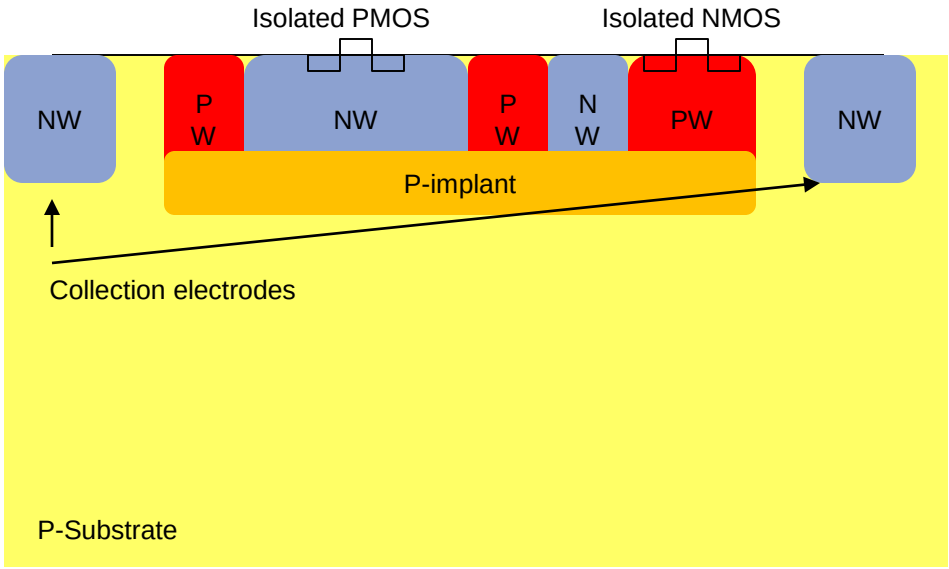




MuPix8, all AMS H18 sensors except „IsoSimple“

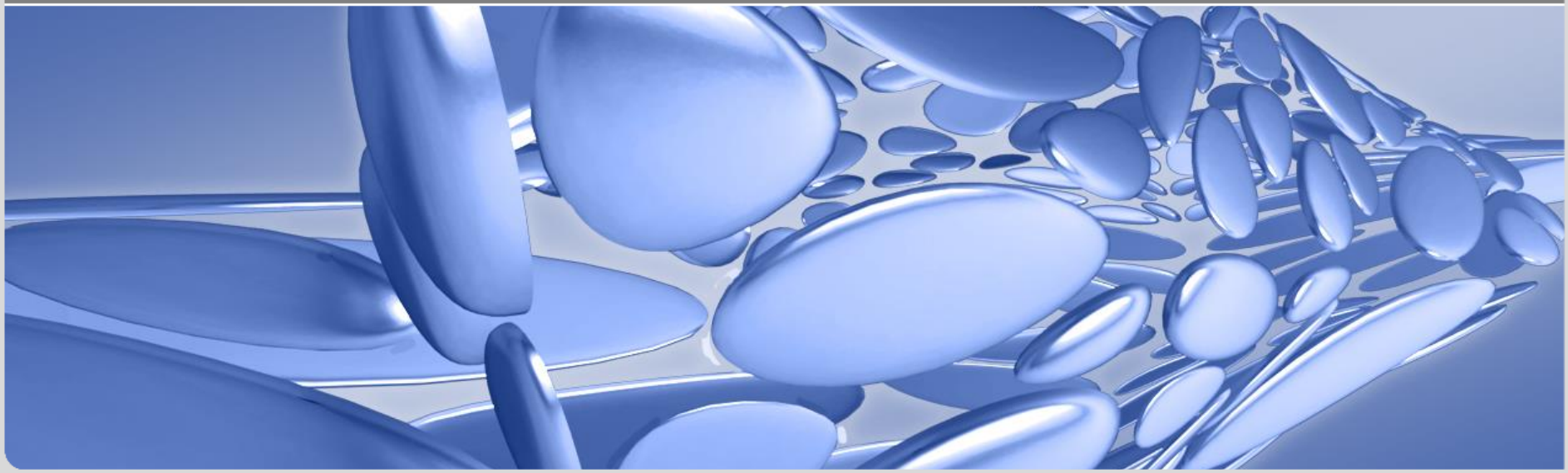


IsoSimple in AMS aH18 and all LFA15 sensors

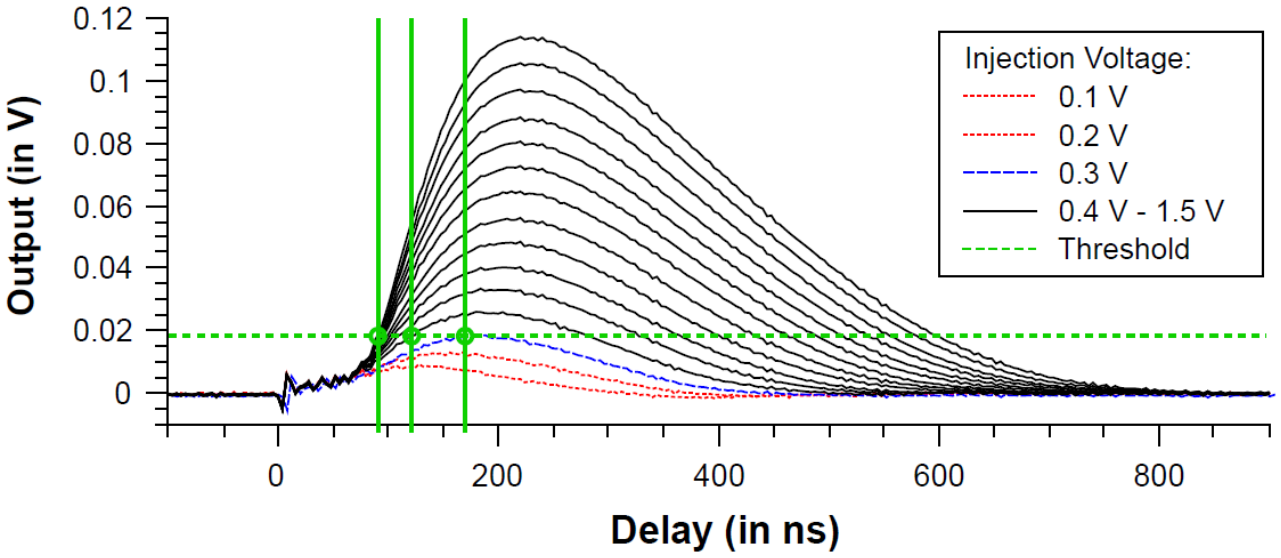


One ATLASPix type in LFA15

Analog measurements and time-walk

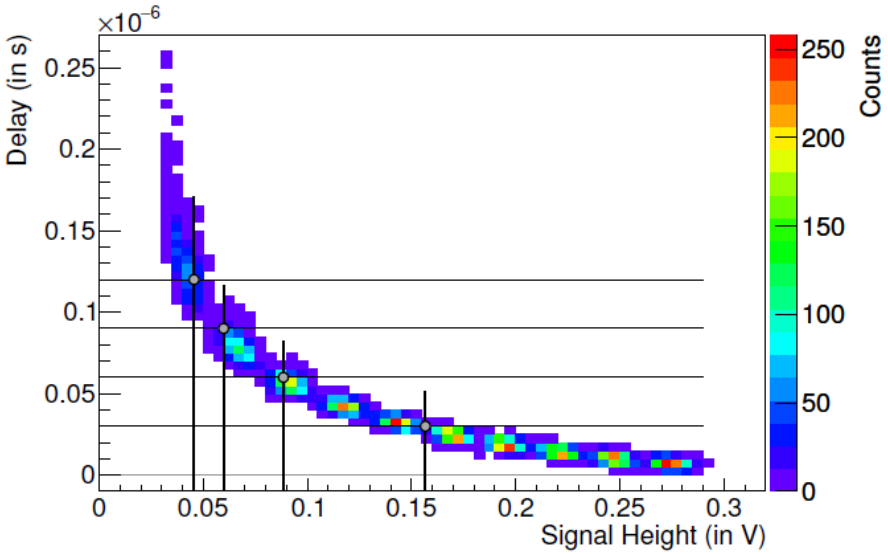


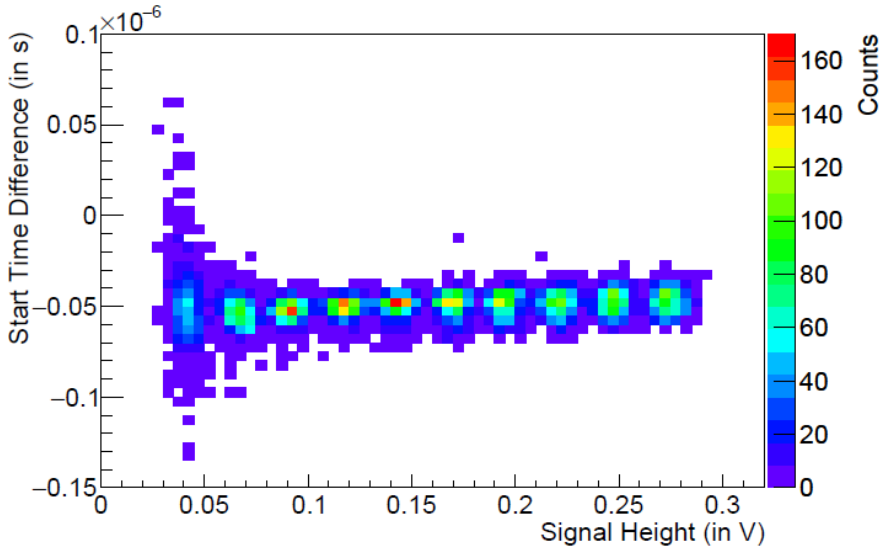
- Motivation: correction of time walk
- Example: Measurements done on HVStrip (R. Schimassek, F Ehrler, NSS MIC 2016)
- Following methods for TW correction investigated: double threshold, 6-point sampling, TW compensating comparator



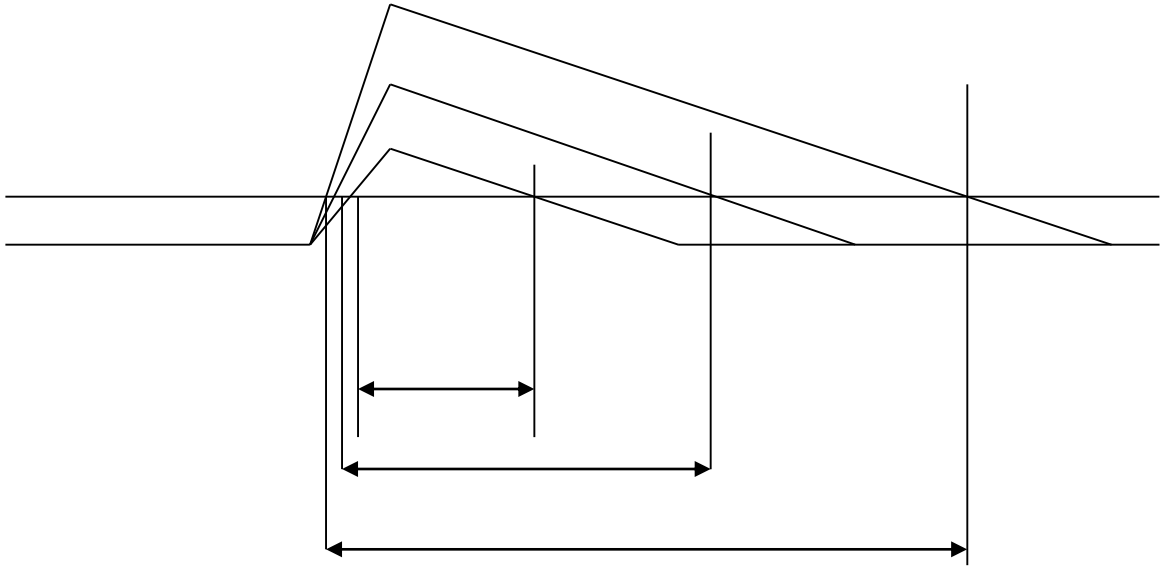
F. Ehrler, “Development of active CMOS sensors for particle physics experiments”, KIT (2015).

- Plain time-walk and jitter (1000e to 7300e) 170ns (6 sigma)
- Several height measurements 100ns
- Sampling with 6 points 100ns

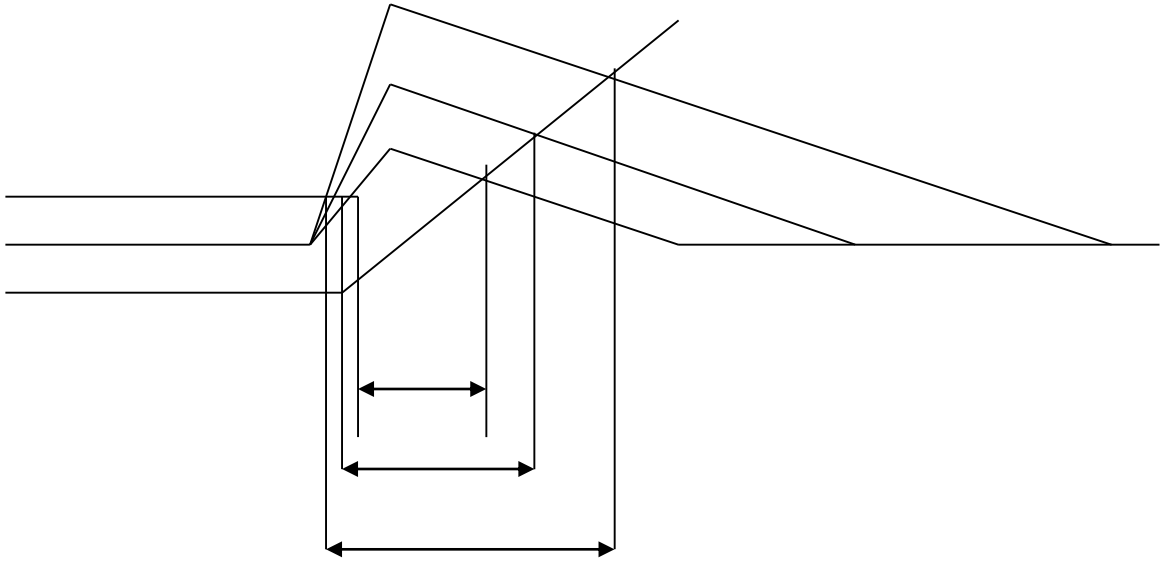




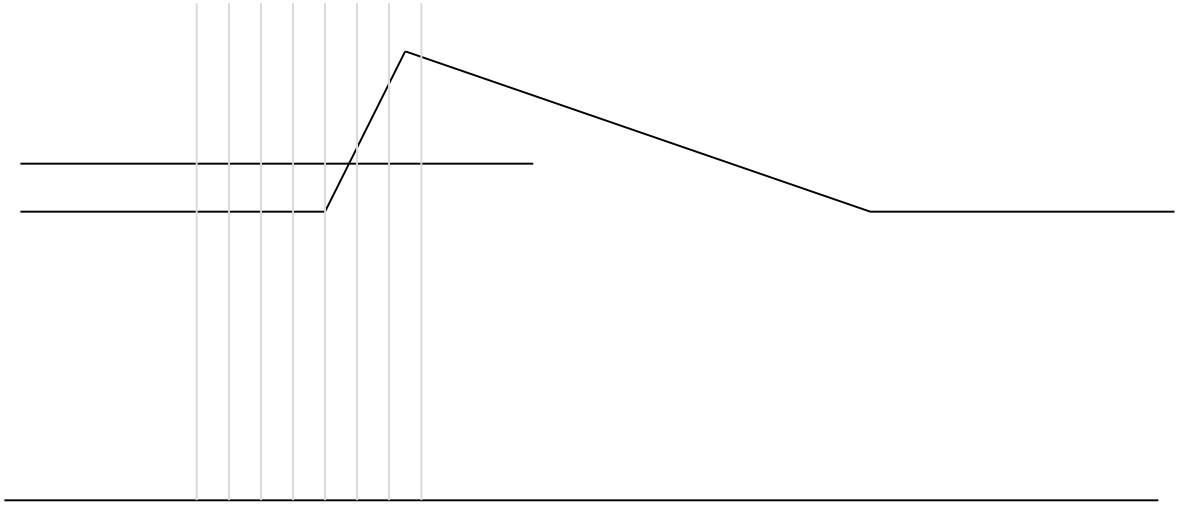
- Amplitude Measurement: ToT (as in MuPix8)



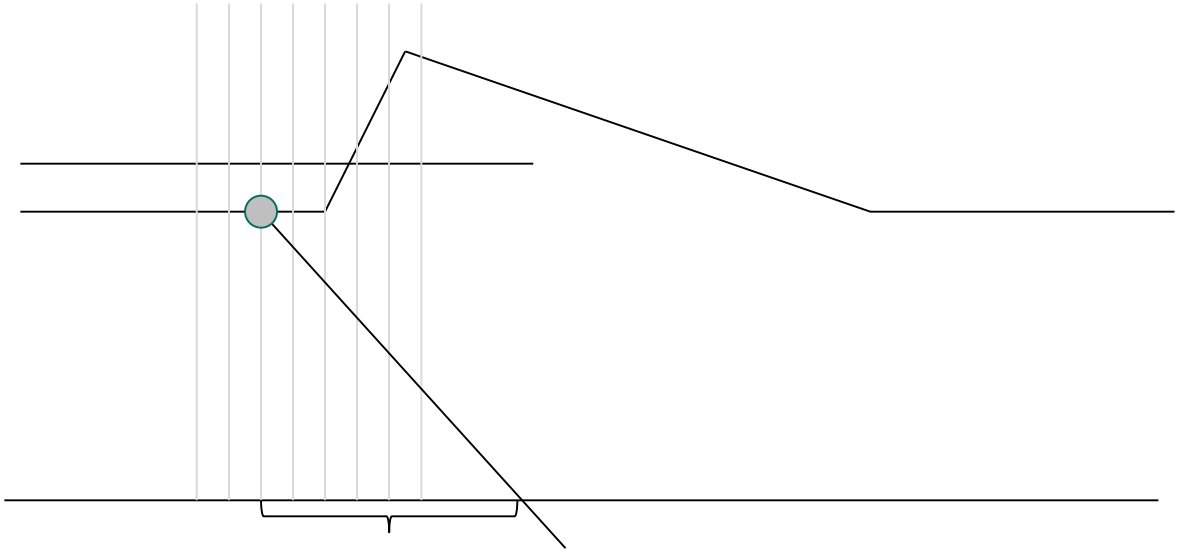
- Amplitude Measurement: Ramp (MuPix8)



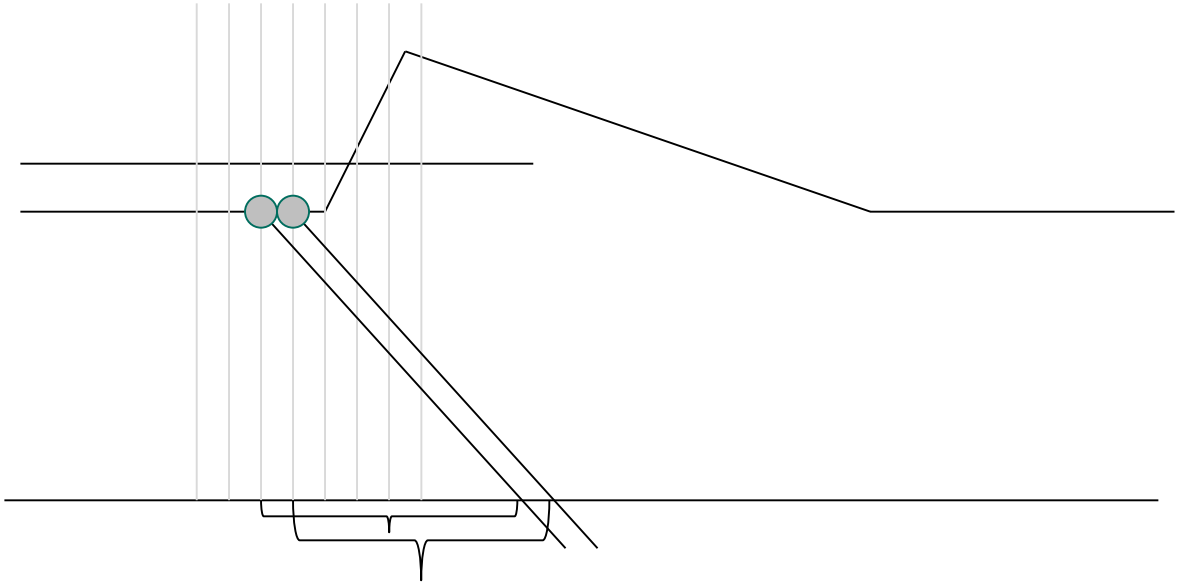
- Amplitude Measurement: Sampling (WavePix)



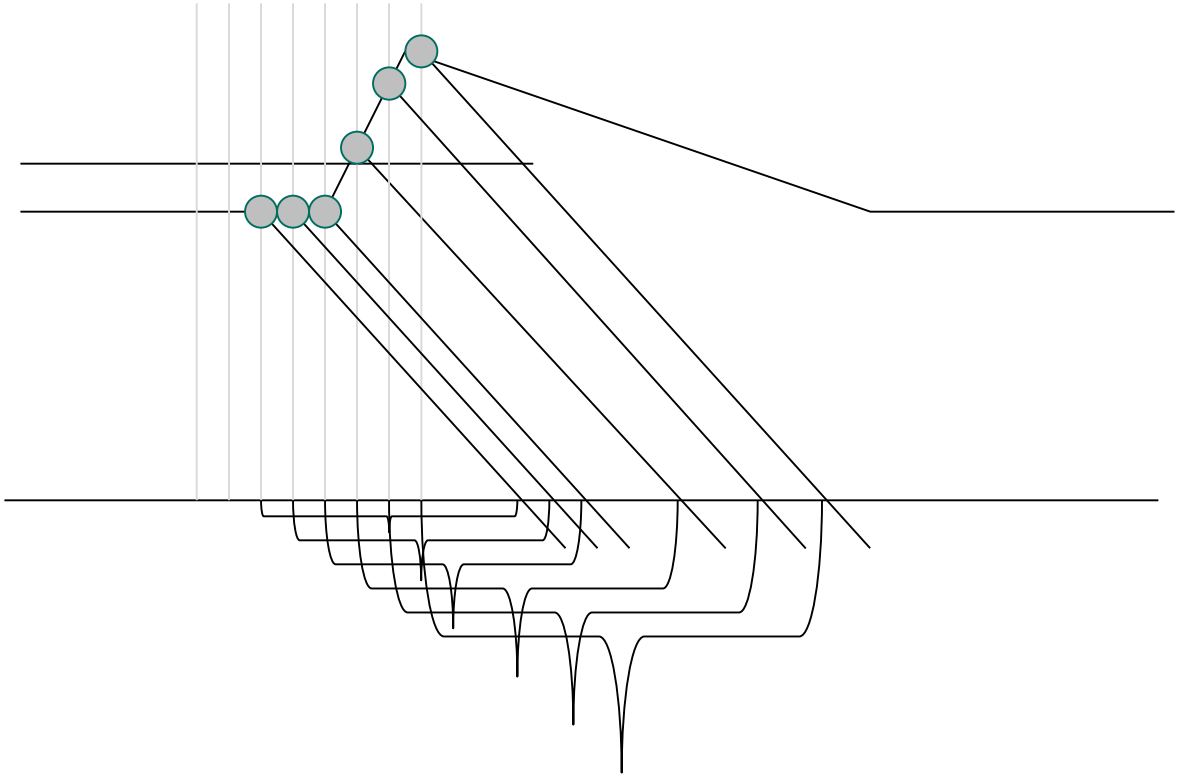
- Amplitude Measurement: Sampling



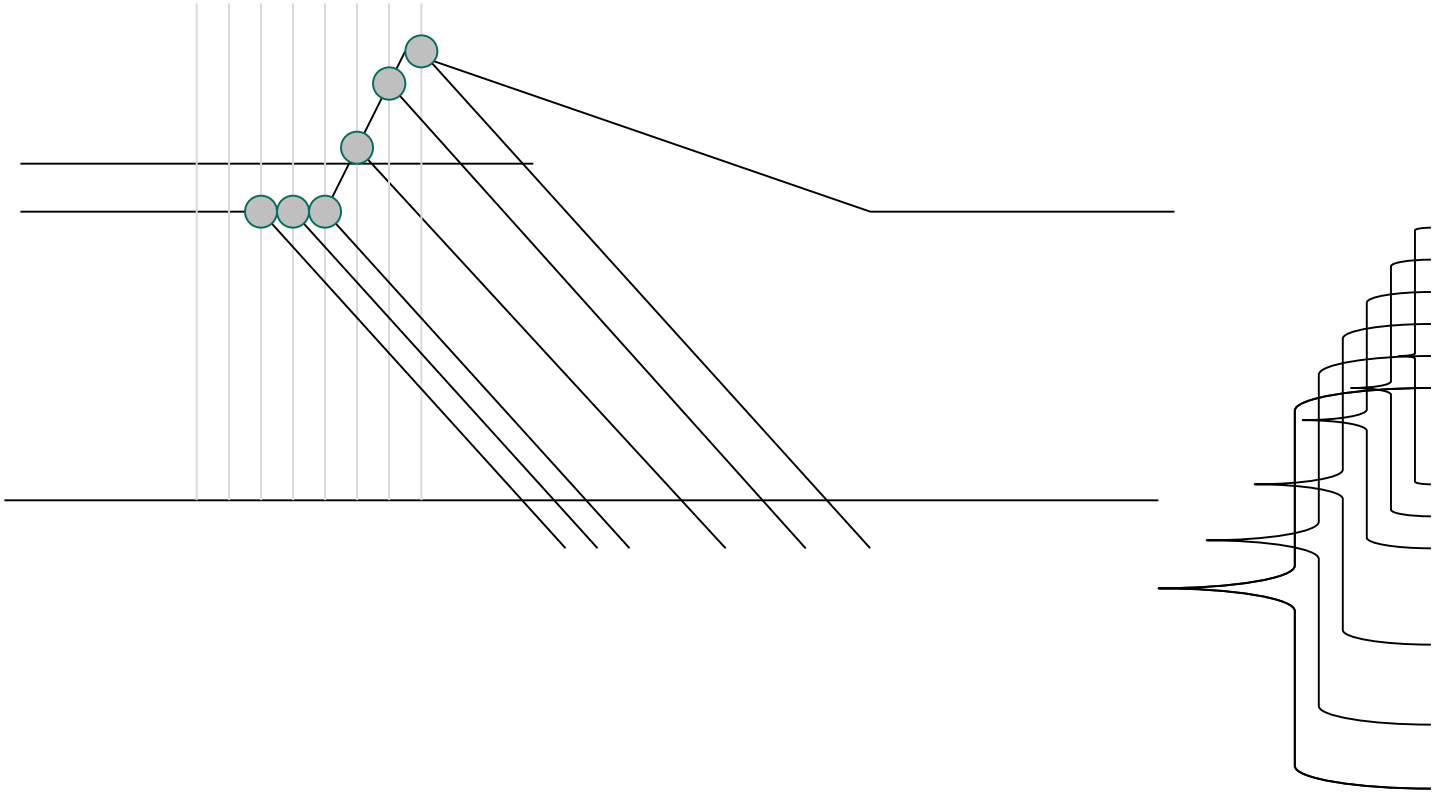
- Amplitude Measurement: Sampling



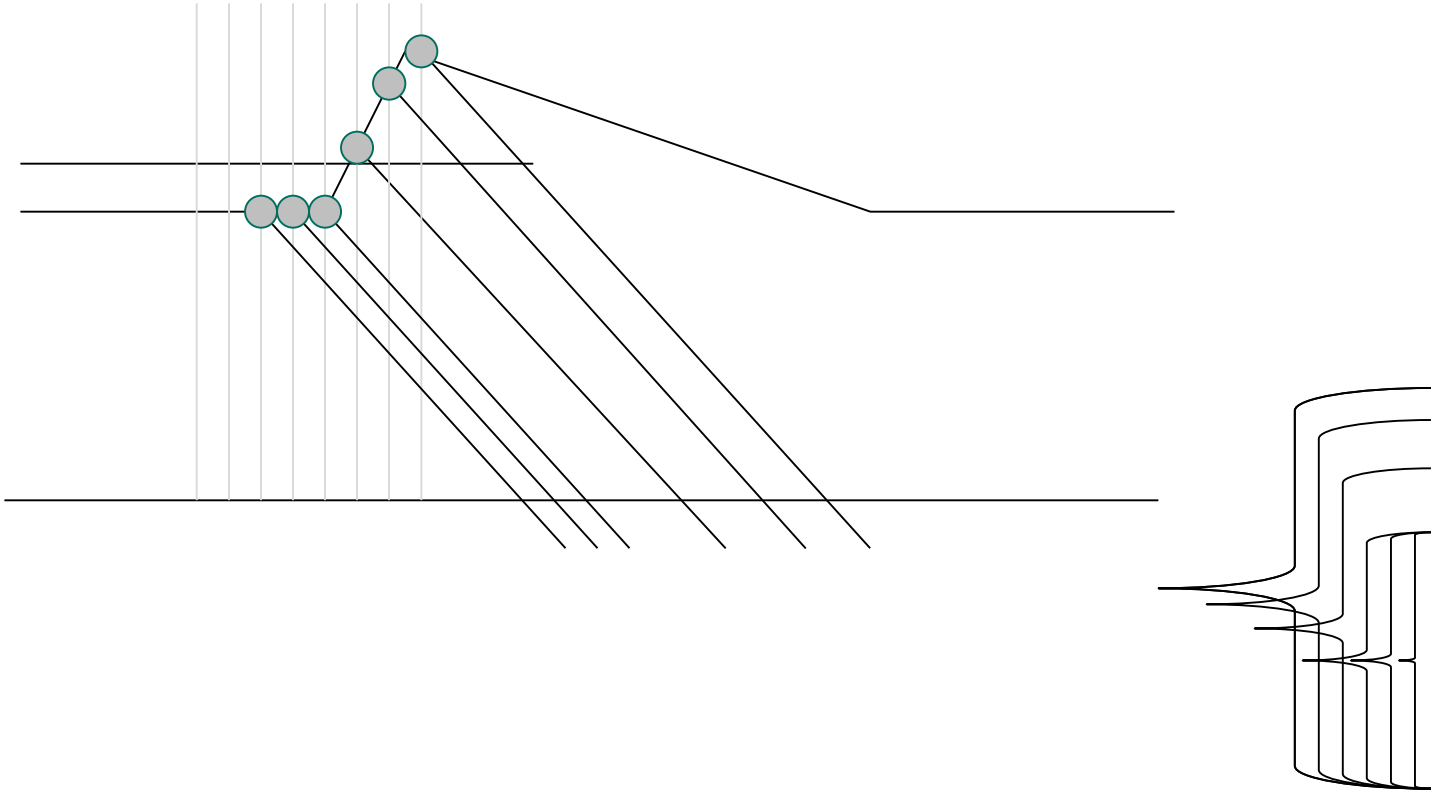
- Amplitude Measurement: Sampling



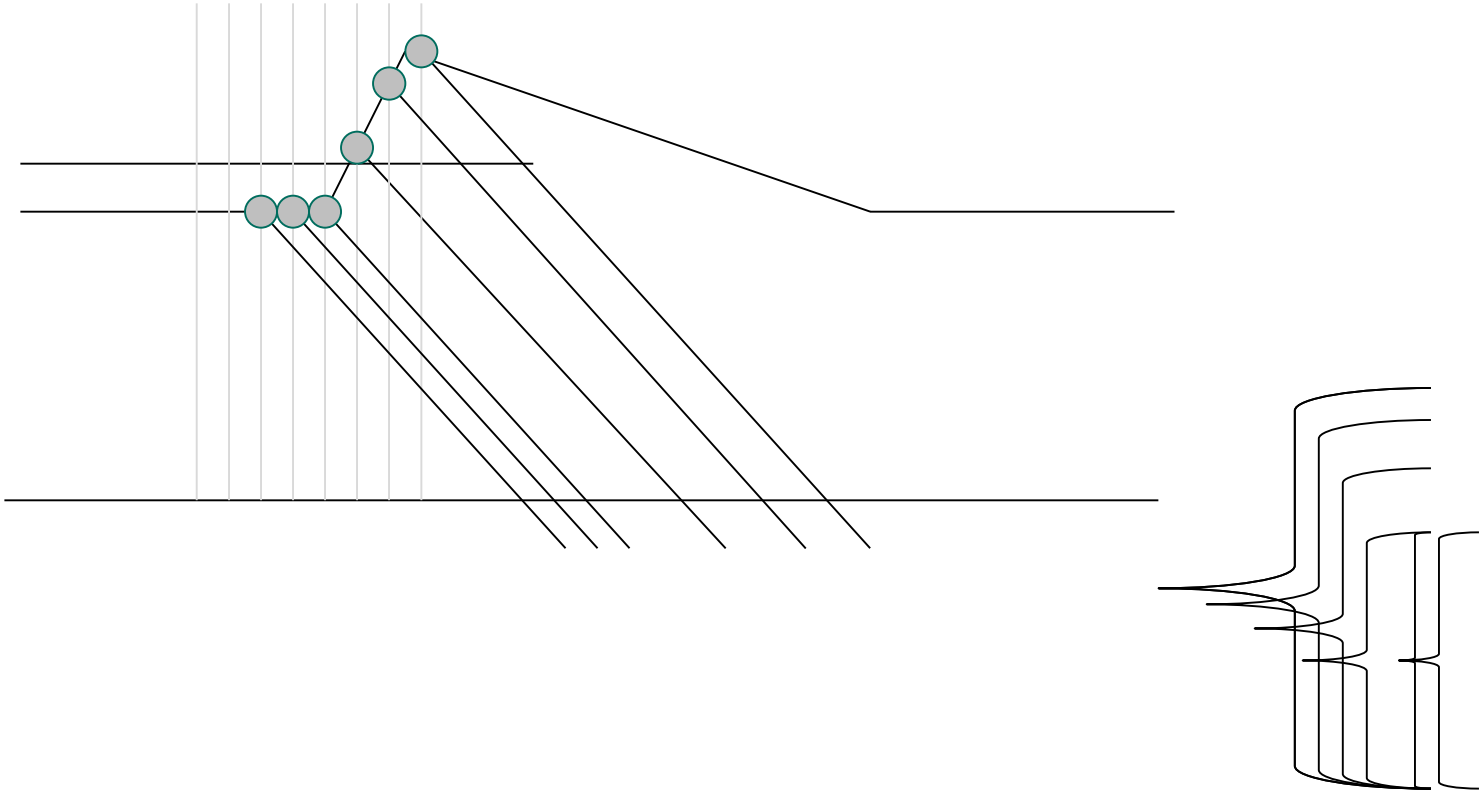
- Amplitude Measurement: Sampling



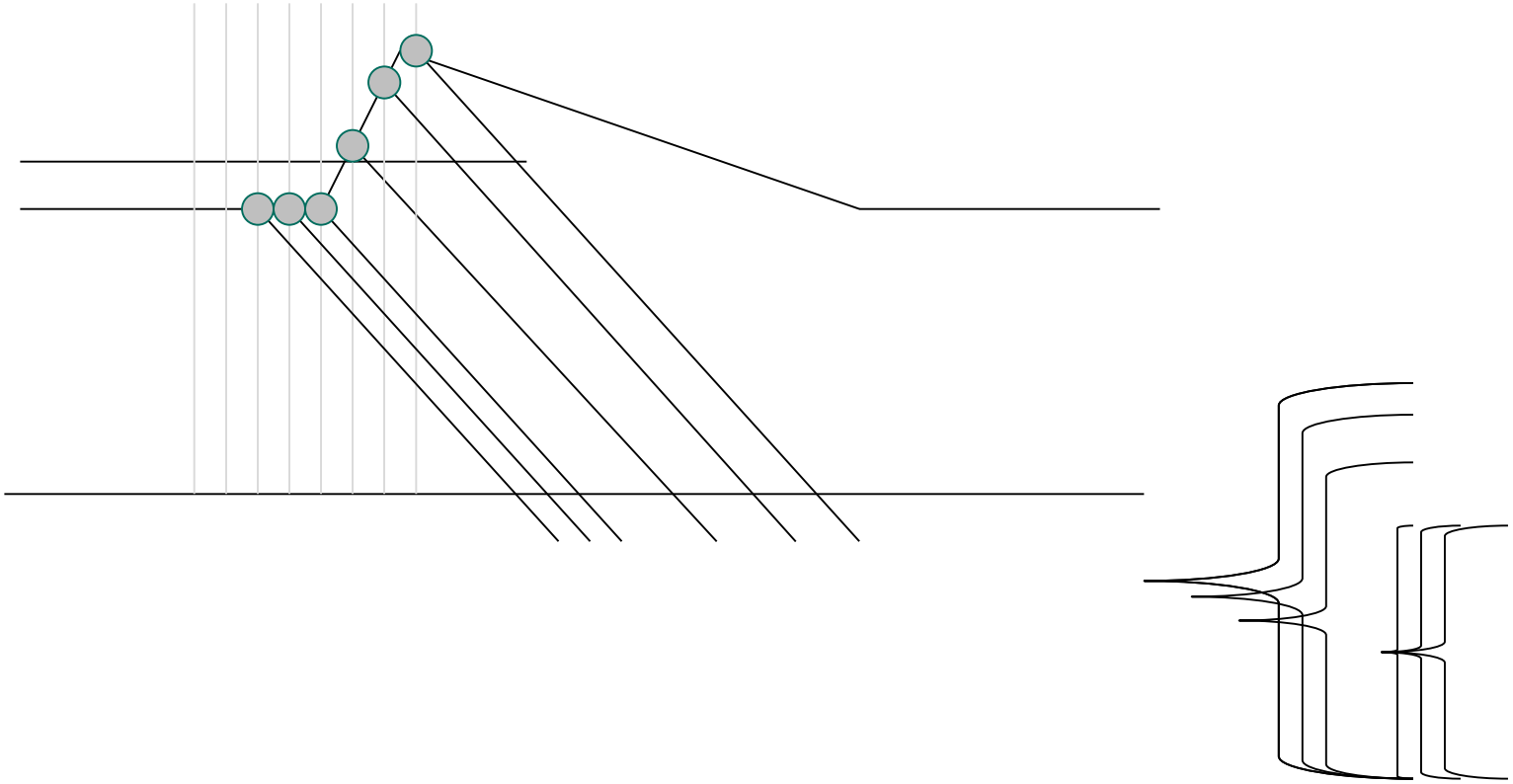
- Amplitude Measurement: Sampling



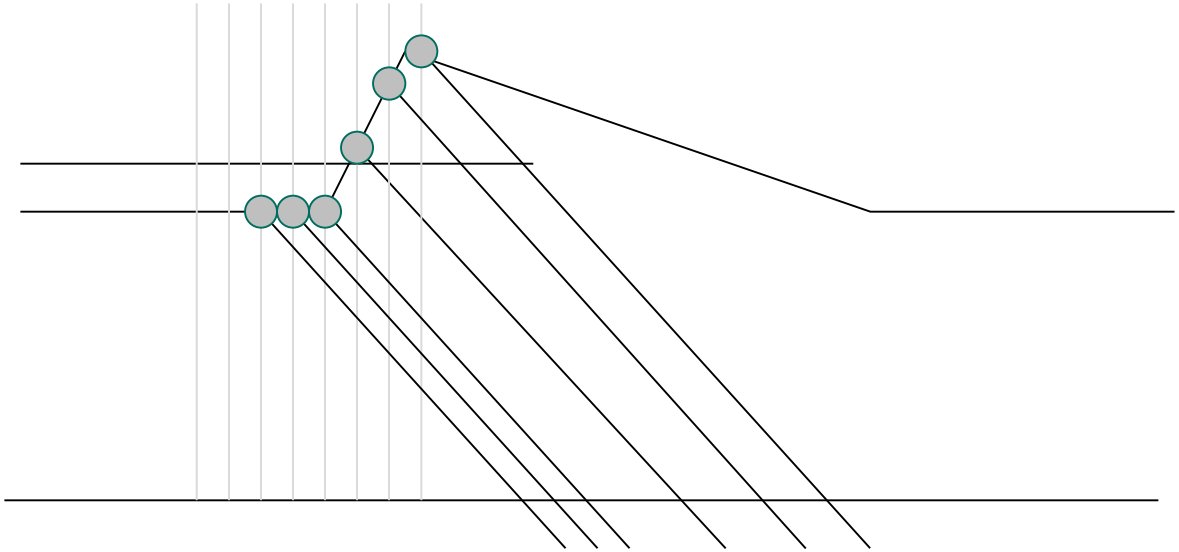
- Amplitude Measurement: Sampling

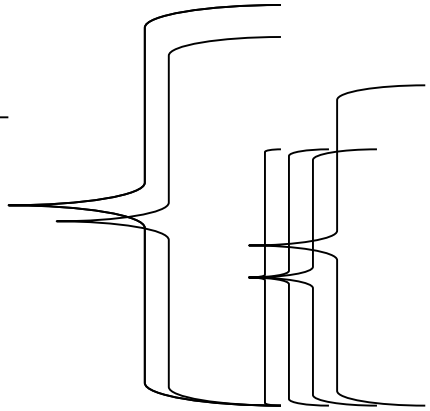


- Amplitude Measurement: Sampling

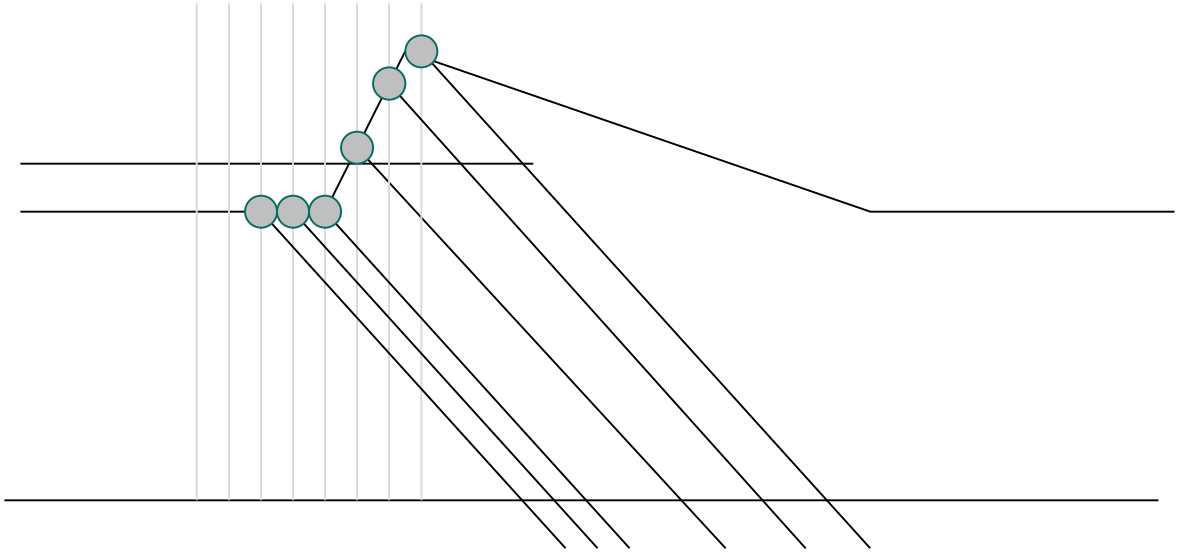


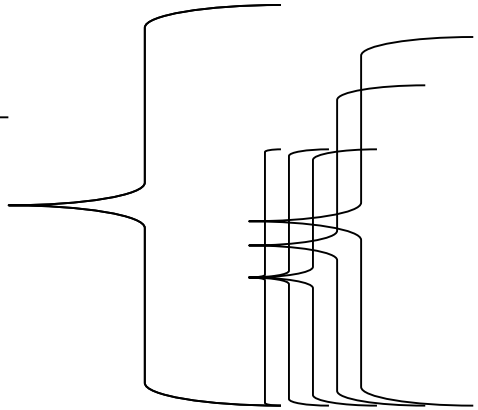
- Amplitude Measurement: Sampling



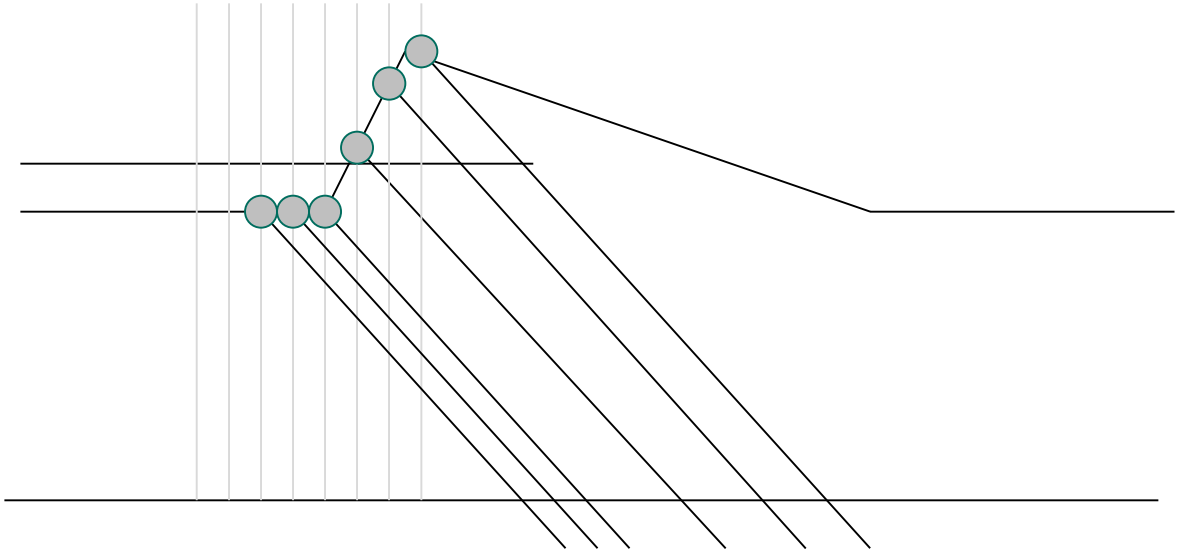


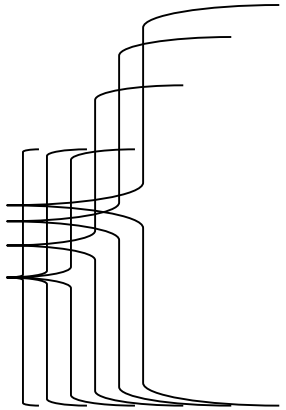
- Amplitude Measurement: Sampling



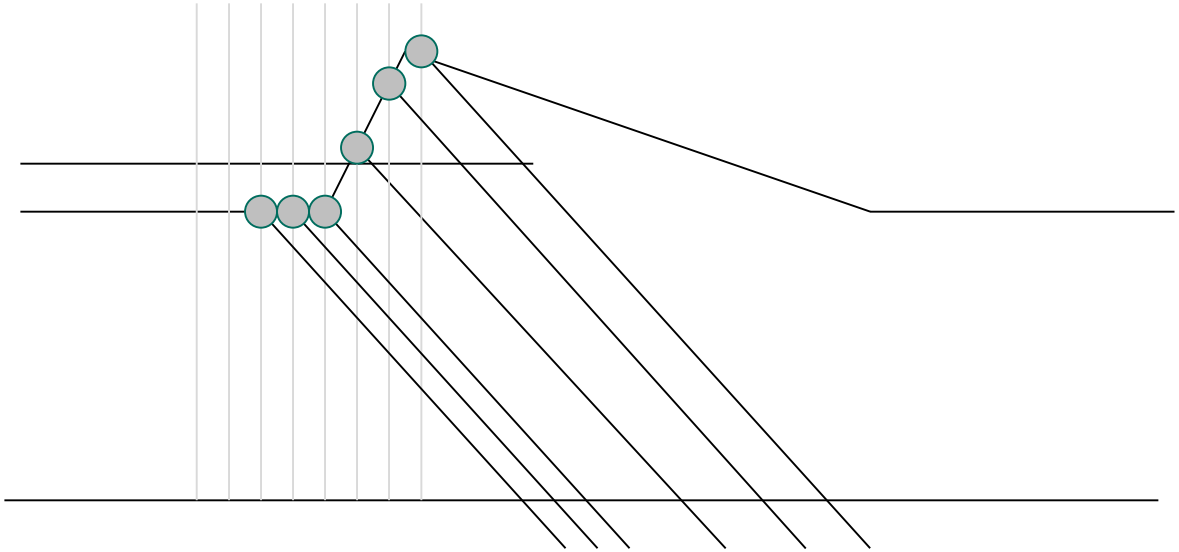


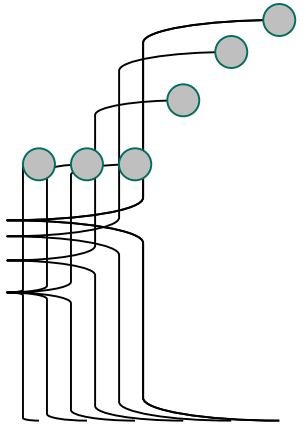
- Amplitude Measurement: Sampling



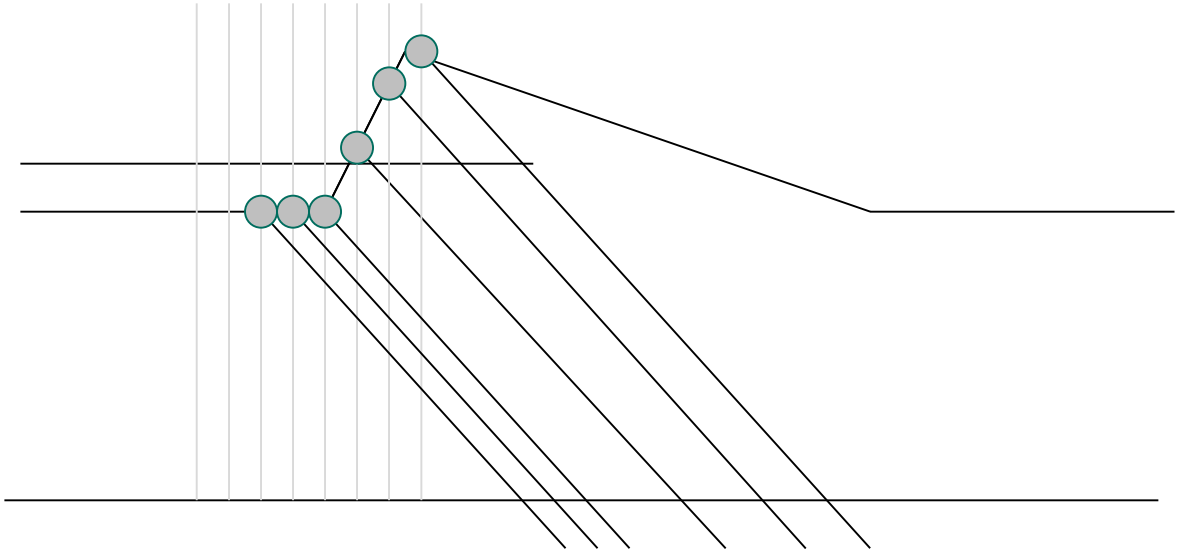


- Amplitude Measurement: Sampling

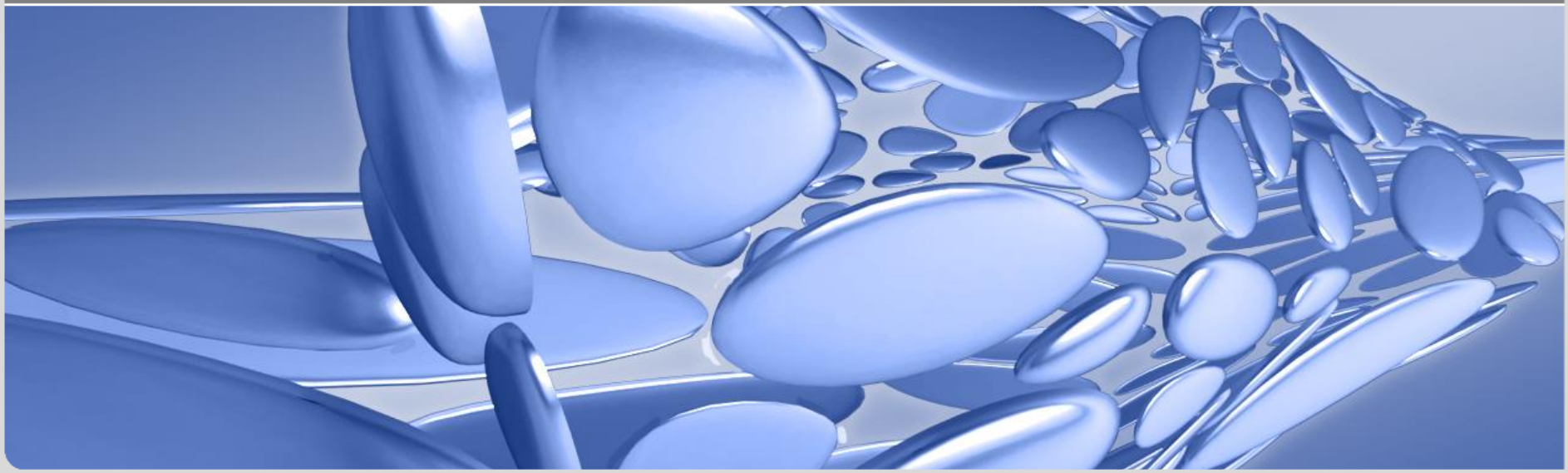




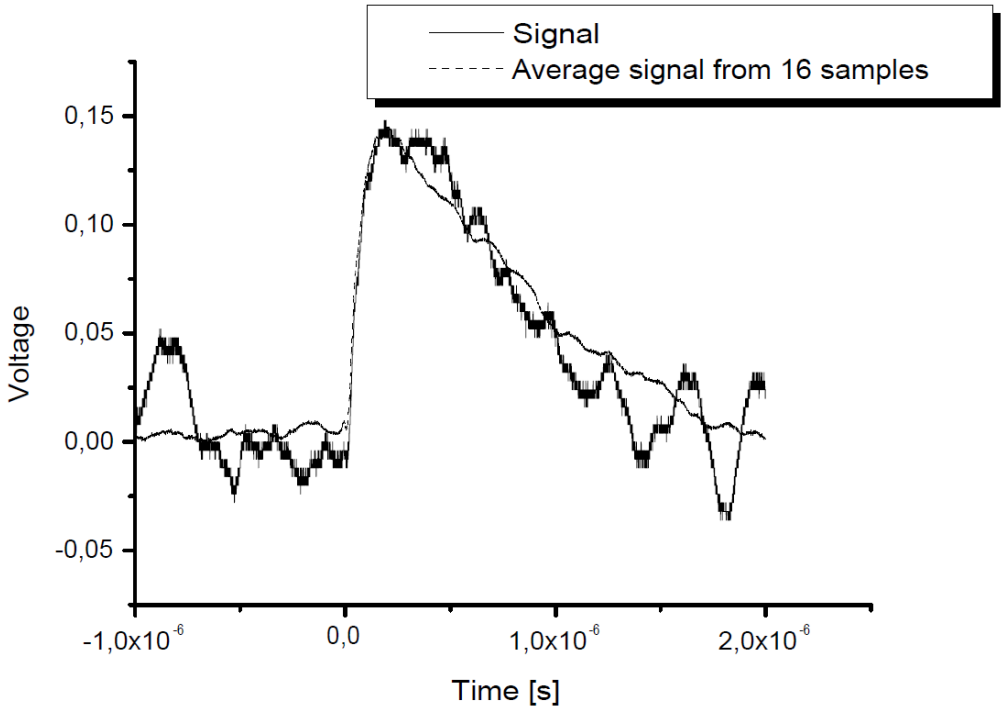
- Amplitude Measurement: Sampling



One experimental result



- Experimental results
- LF_ATLASPIX has been produced, first tests show that electronics works well
- Response to test injection amplitude of 0.5V, that yields to a charge signal of about 1800 e

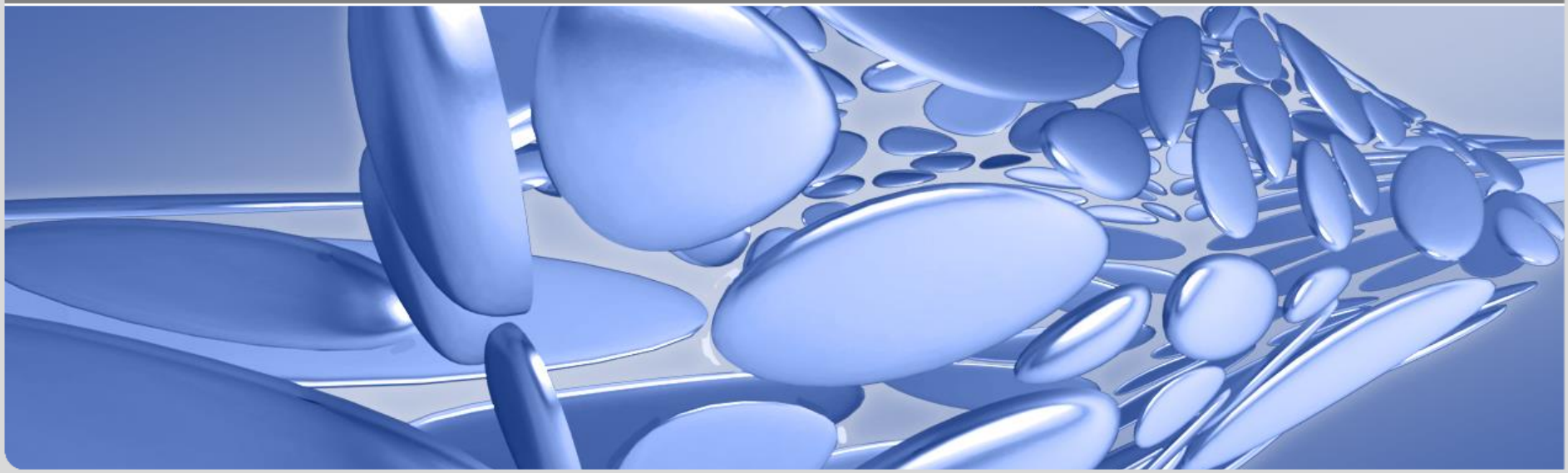


Summary

- Large area HVCMOS monolithic and CCPD sensors for Mu3e and ATLAS experiments have been presented
- Three engineering runs: AMS H35 (H35DEMO), AMS aH18 (ATLASPix, MuPix), LFA15 (LF_ATLASPix)
- Different sensor variants have been designed – triggered and trigerless readout, amplitude measurements by means of ToT or with a ramp, sampling circuit, small and large sensor diodes
- Good results in beam tests with smaller prototypes
- Results with larger prototypes will be presented in separated talks
- CCPD sensors of second generation

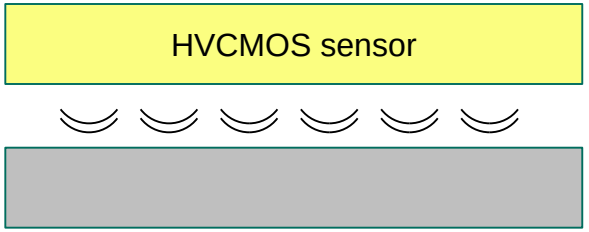
- More…

CCPD



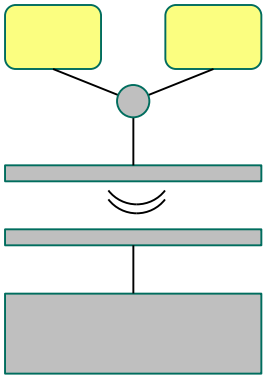
- Why CCPD
- More space for readout electronics - high rate readout and high spatial resolution possible

Monolithic

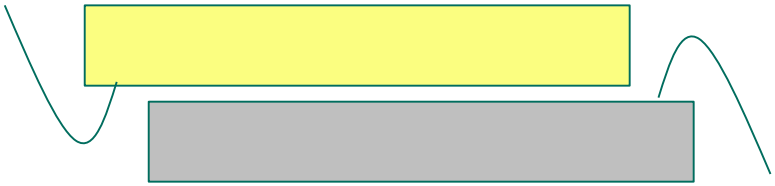


CCPD

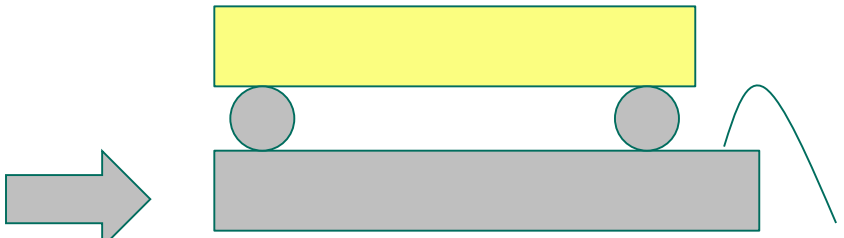
- Coupling of many pixels to one readout channels -> smaller sensor pixels



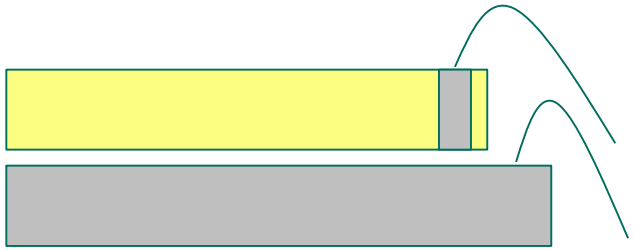
- First generation of CCPDs
- Amplitude encoding of pixel position -> difficult with typical 4-bit resolution of used ROCs
- Two side wire bonding needed



- CCPDs of senond generation

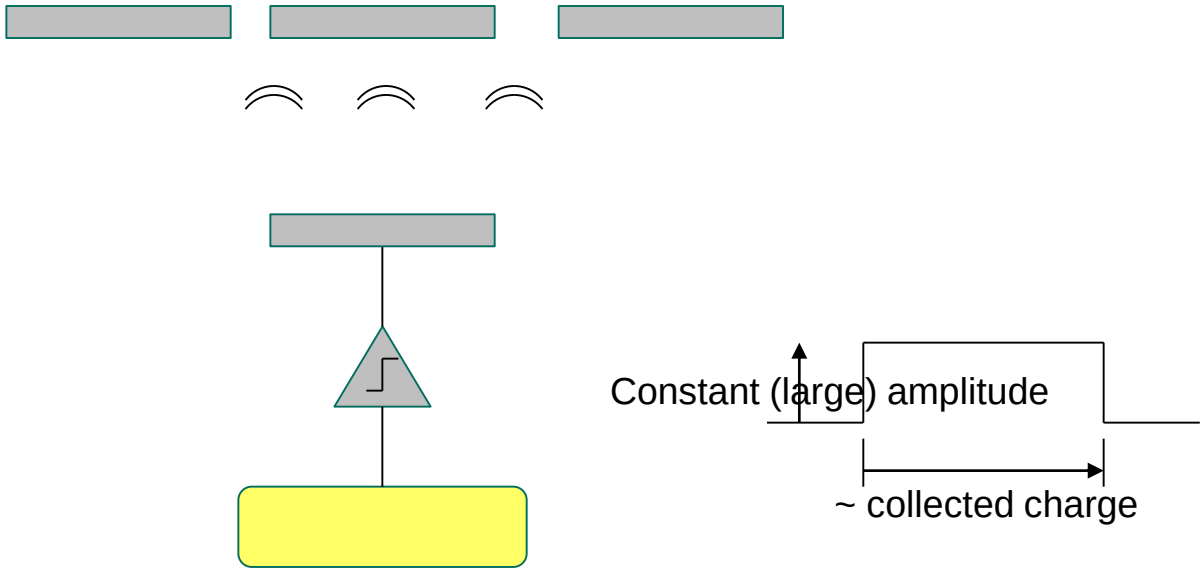


CCPD with a few standard bumps

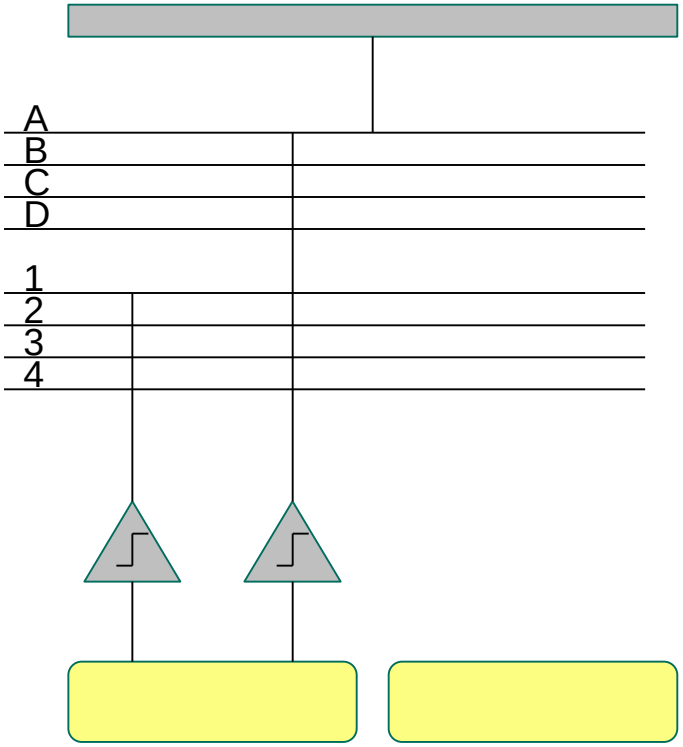


CCPD with TSVs

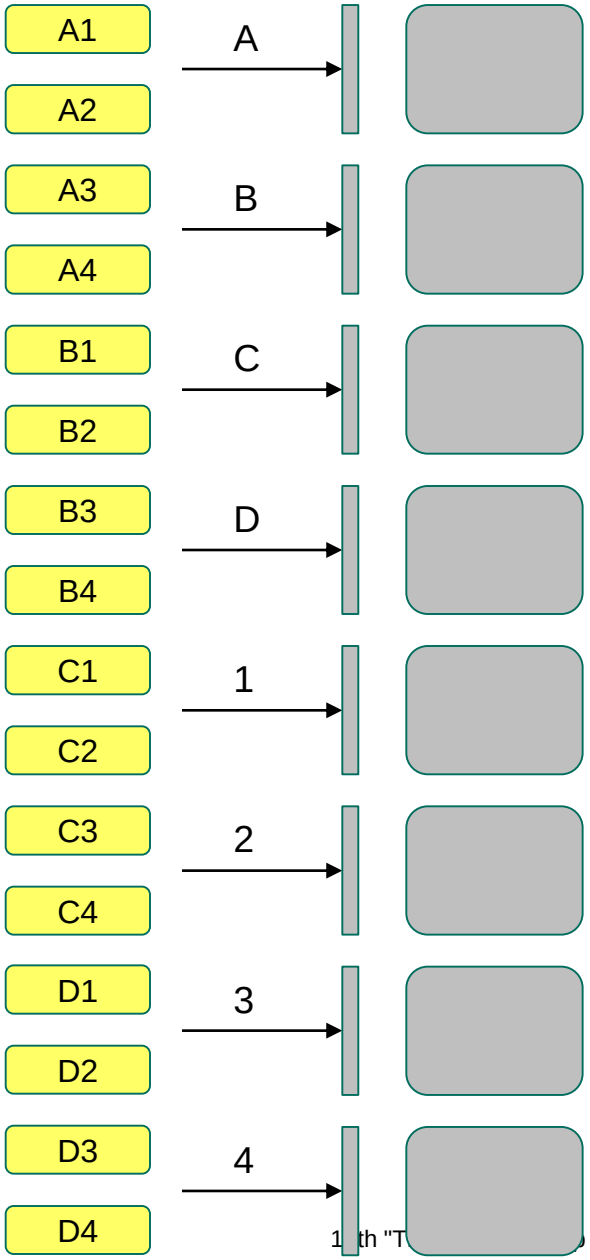
- Pixels with digital output
- Transmission over larger gap possible
- No crosstalk
- Compatible with existing ROCs
- Information about collected charge preserved



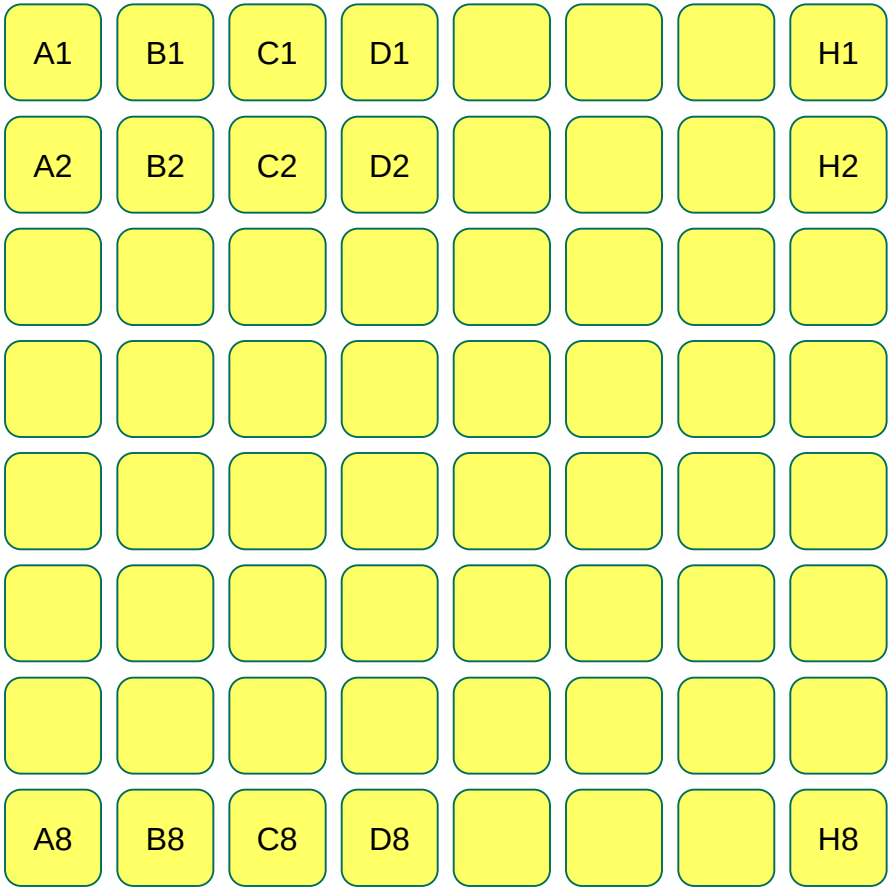
- Spatial resolution enhancement



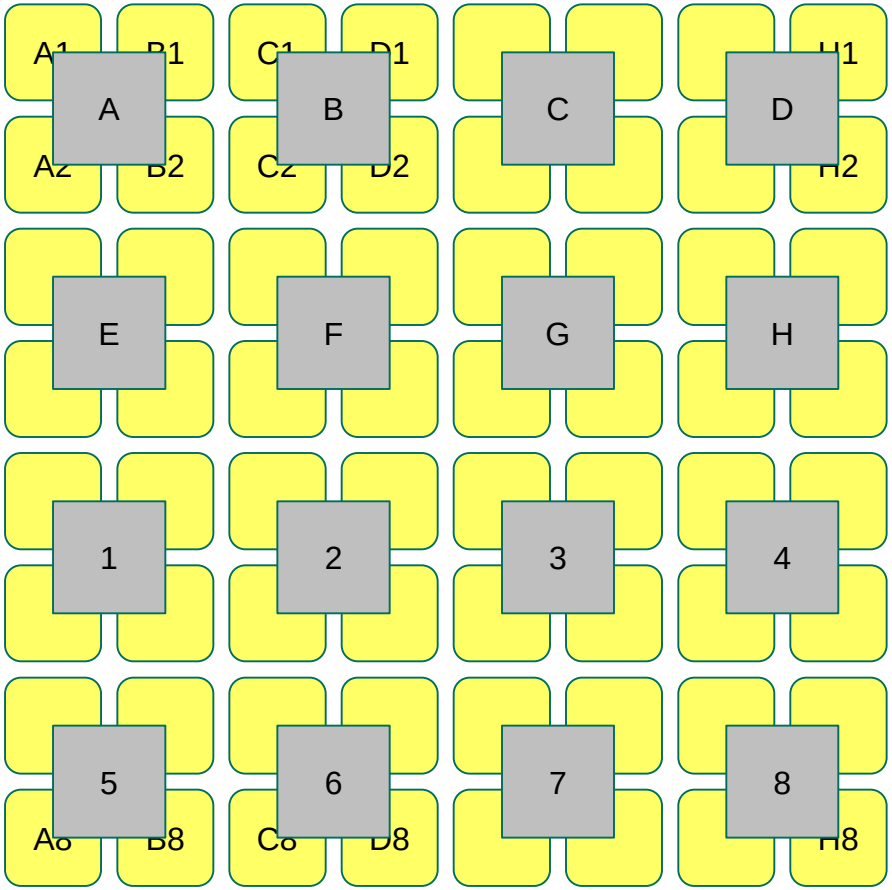
- Spatial resolution enhancement
- Pad/pixel area ratio – 2x



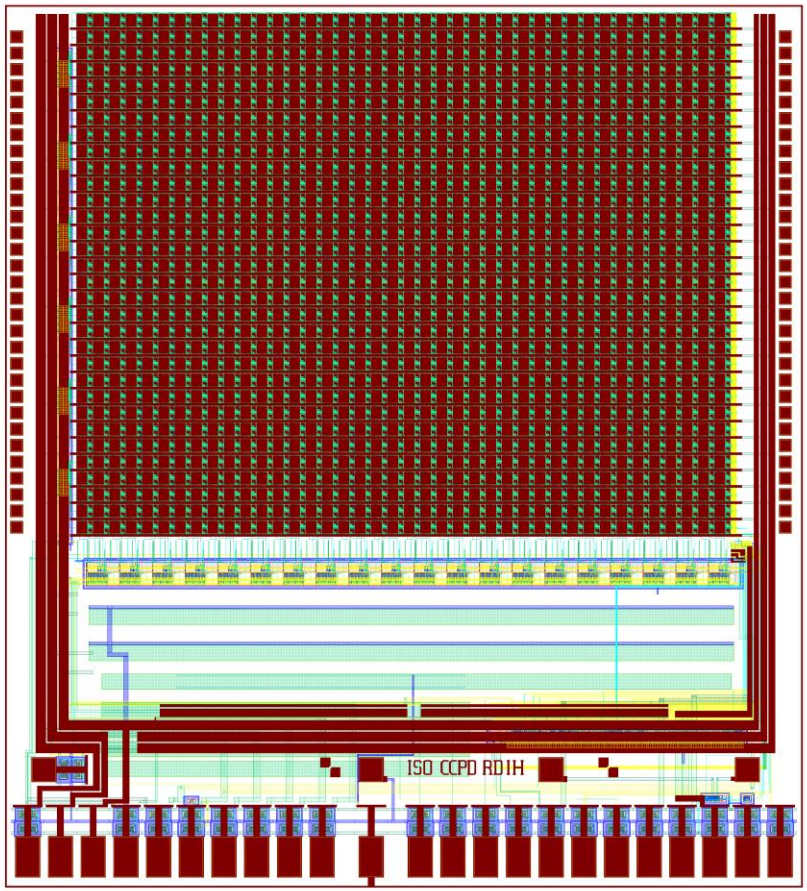
- Spatial resolution enhancement
- Pad/pixel area ratio – 4x

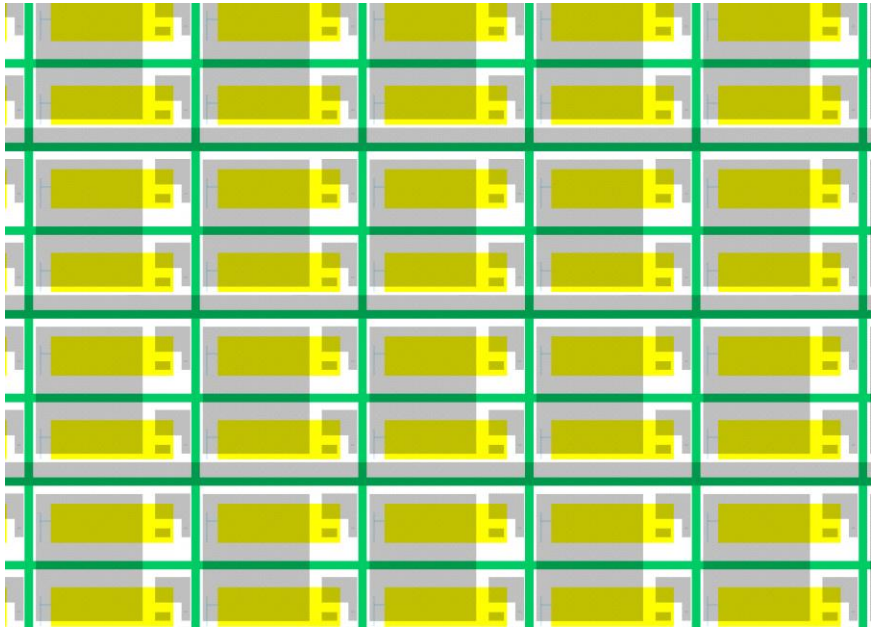


- Spatial resolution enhancement
- Pad/pixel area ratio – 4x

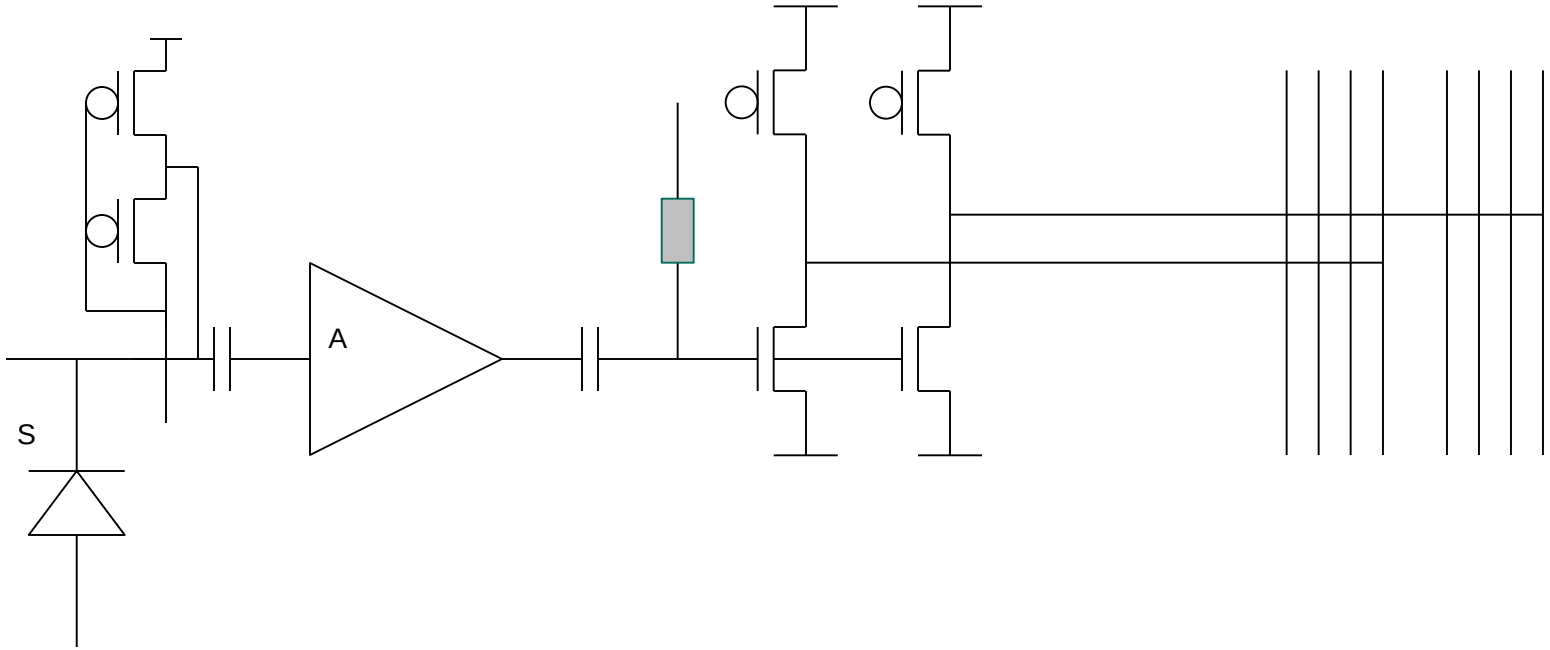


- RD53_CCCD
- Pixel size 25um x 50um, electrode pitch 50um x 50um
- AMS H18

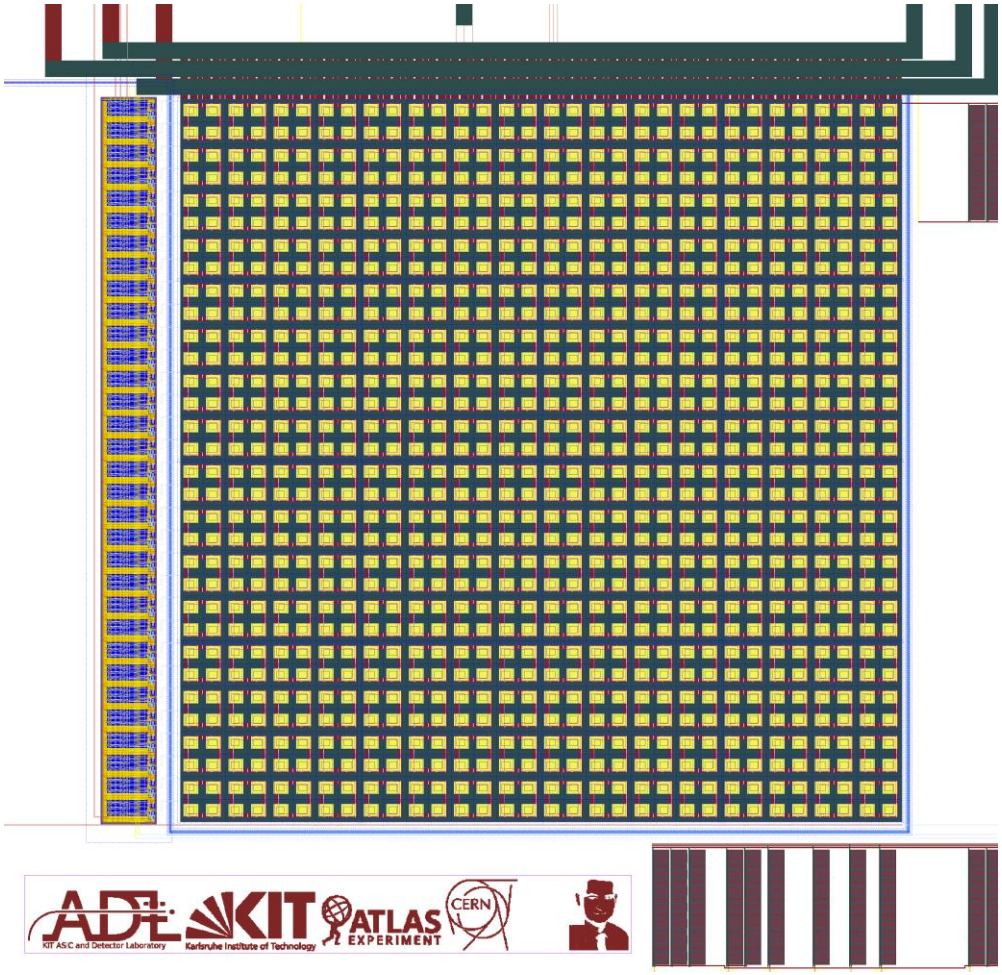


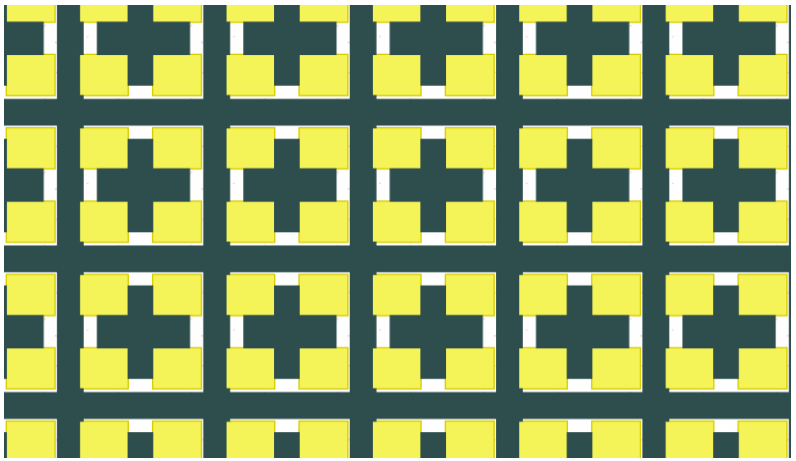


- RD53_CCCD
- Pixel size 25um x 50um, electrode pitch 50um x 50um
- AMS H18

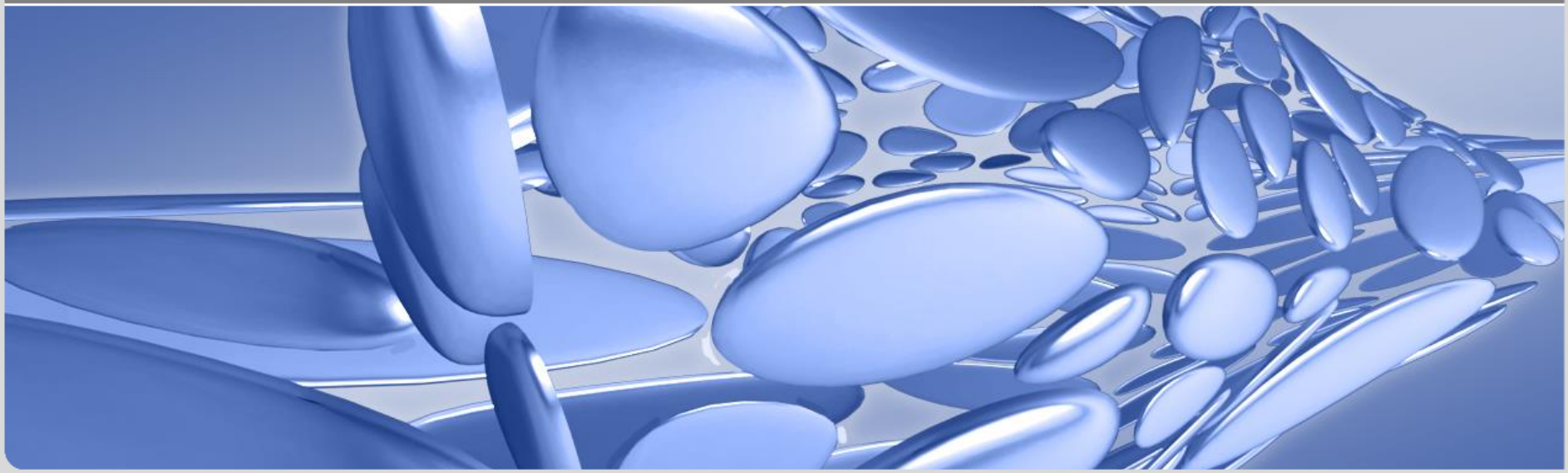


- TP_CCCD
- Pixel size 27.5um x 27.5um, electrode pitch 55um x 55um
- LFA15

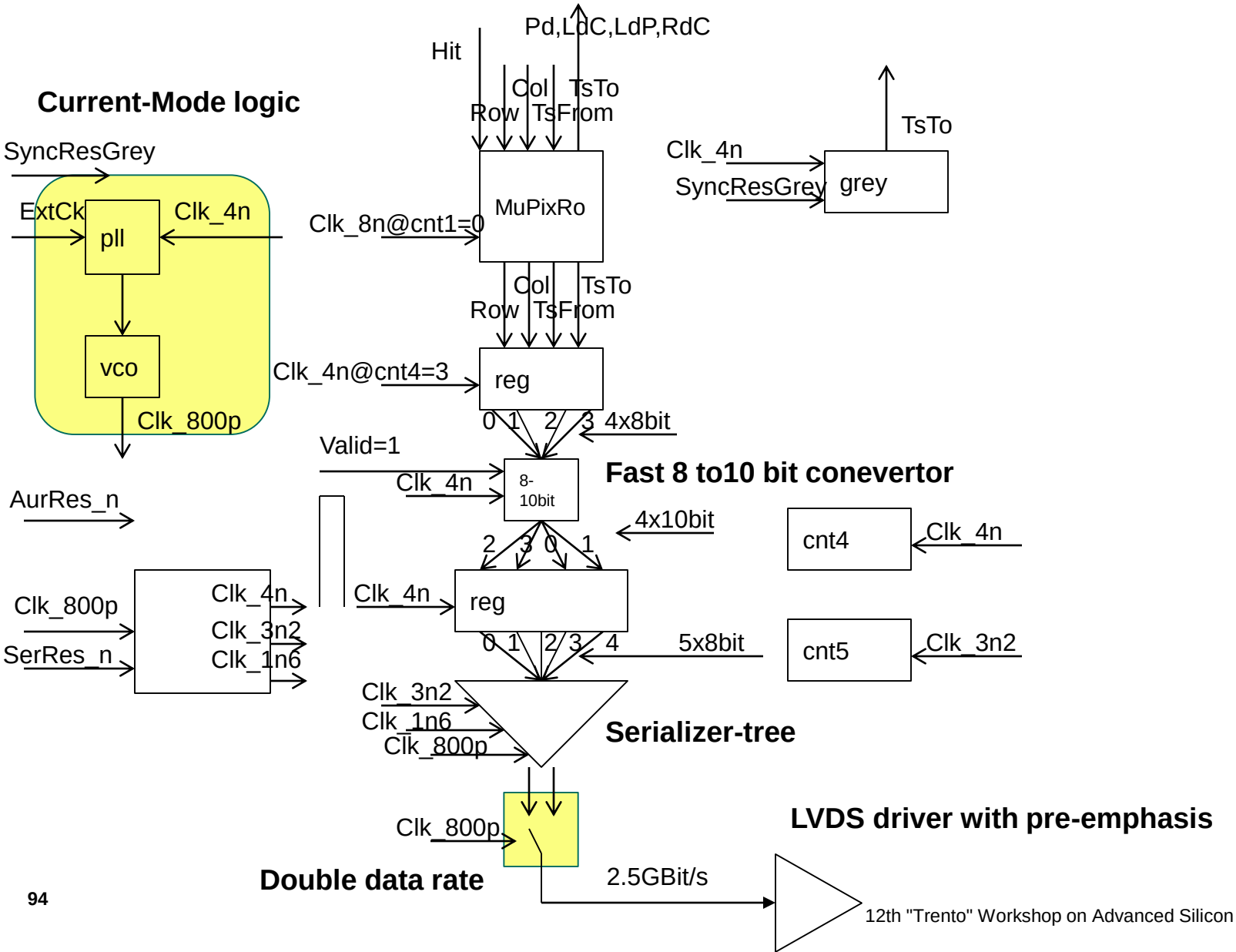




Gbit data transmission in 180nm technology

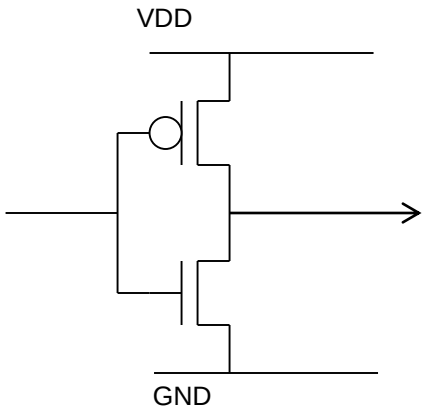


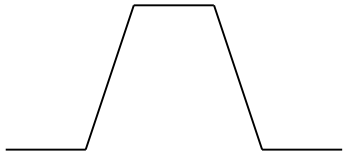
- …


Current-Mode logic
SyncResGrey
ExtCk
pll
Clk_4n
vco
Clk_800p
Pd,LdC,LdP,RdC
Hit
Col
TsTo
Row
TsFrom
Clk_8n@cnt1=0
MuPixRo
Clk_4n
SyncResGrey
grey
TsTo
Col
TsTo
Row
TsFrom
Clk_4n@cnt4=3
reg
0 1 2 3 4x8bit
Valid=1
Clk_4n
8-10bit
Fast 8 to10 bit conevertor
AurRes_n
4x10bit
cnt4
Clk_4n
2 3 0 1
Clk_800p
SerRes_n
Clk_4n
Clk_3n2
Clk_1n6
Clk_4n
reg
0 1 2 3 4
5x8bit
cnt5
Clk_3n2
Clk_3n2
Clk_1n6
Clk_800p
Serializer-tree
Clk_800p
LVDS driver with pre-emphasis
Double data rate
2.5GBit/s

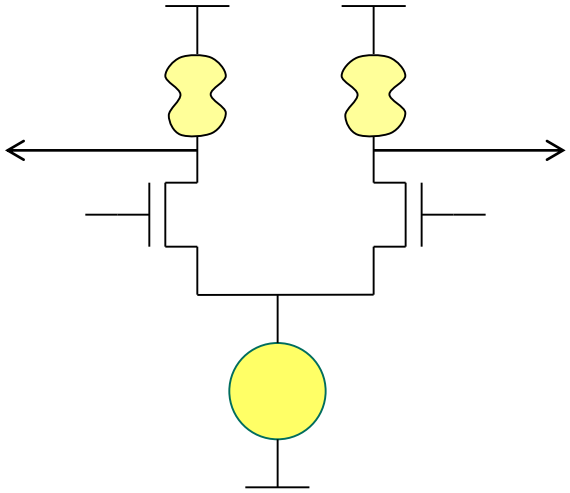
- ...

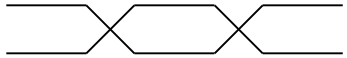
CMOS logic

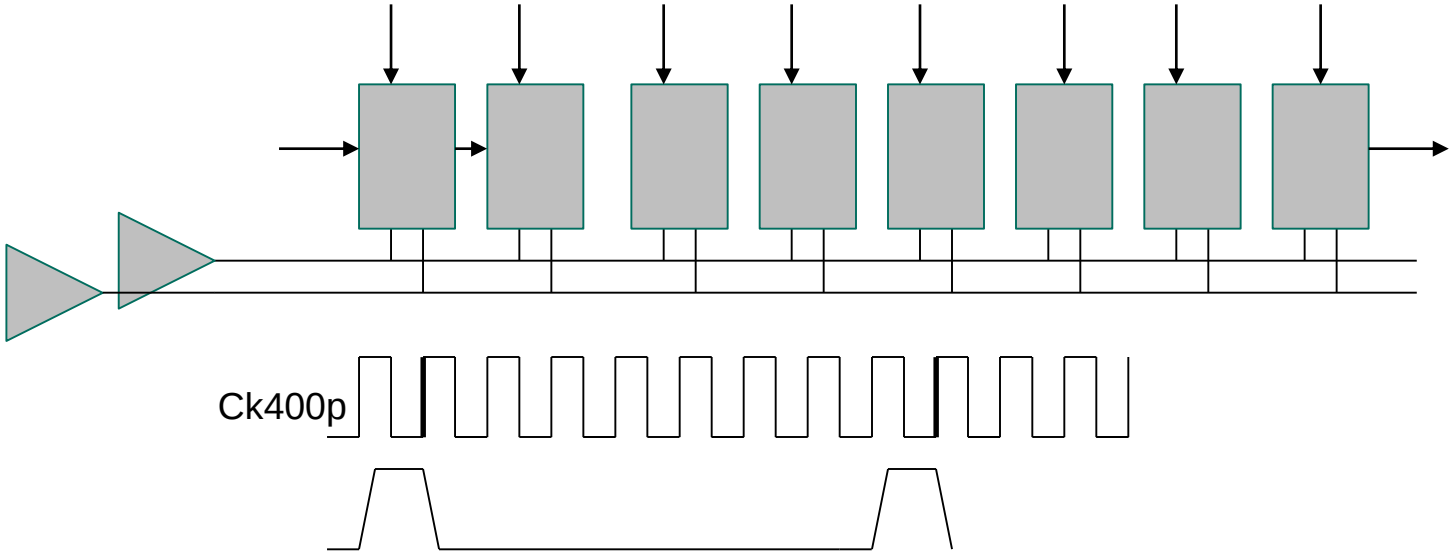


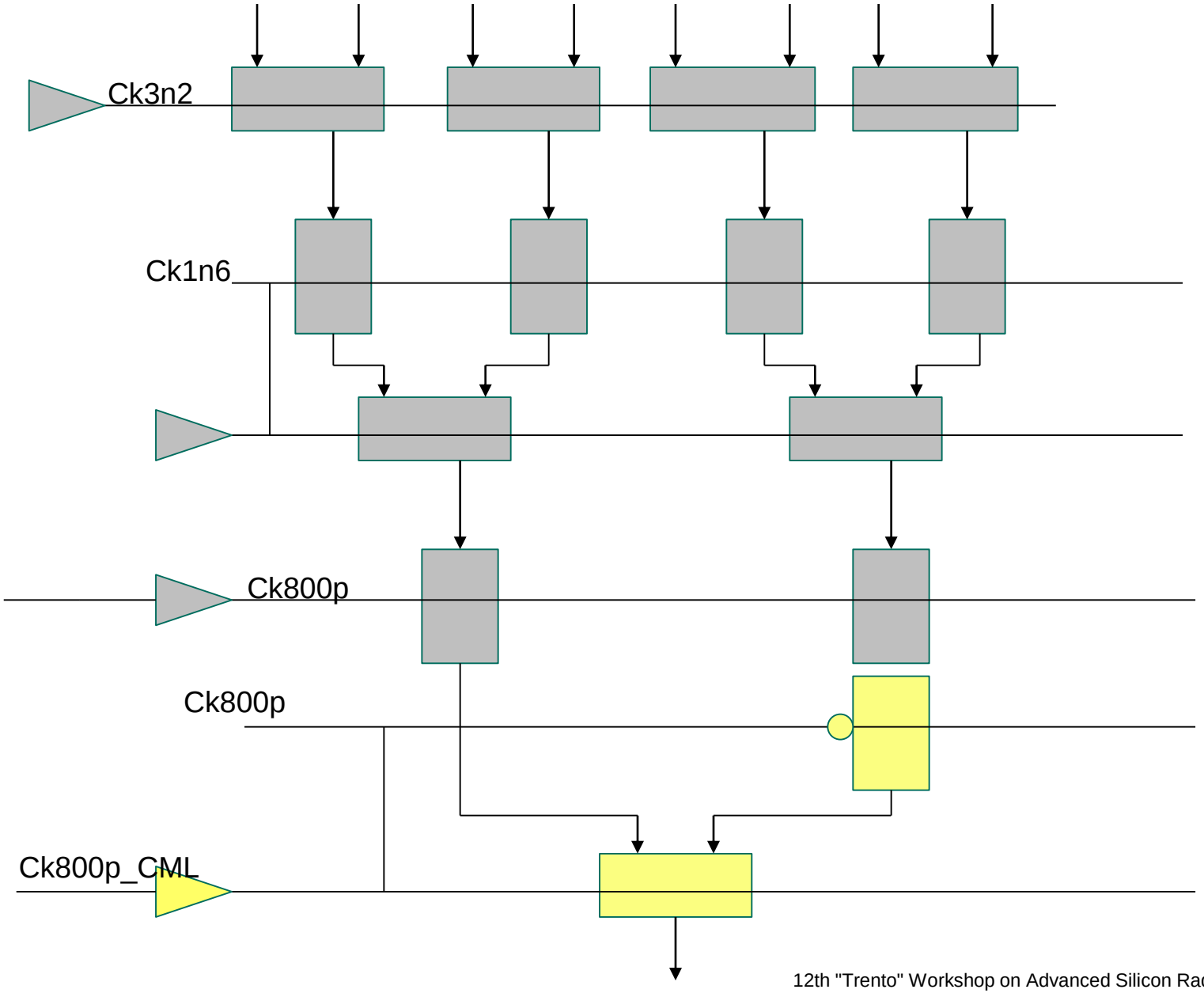


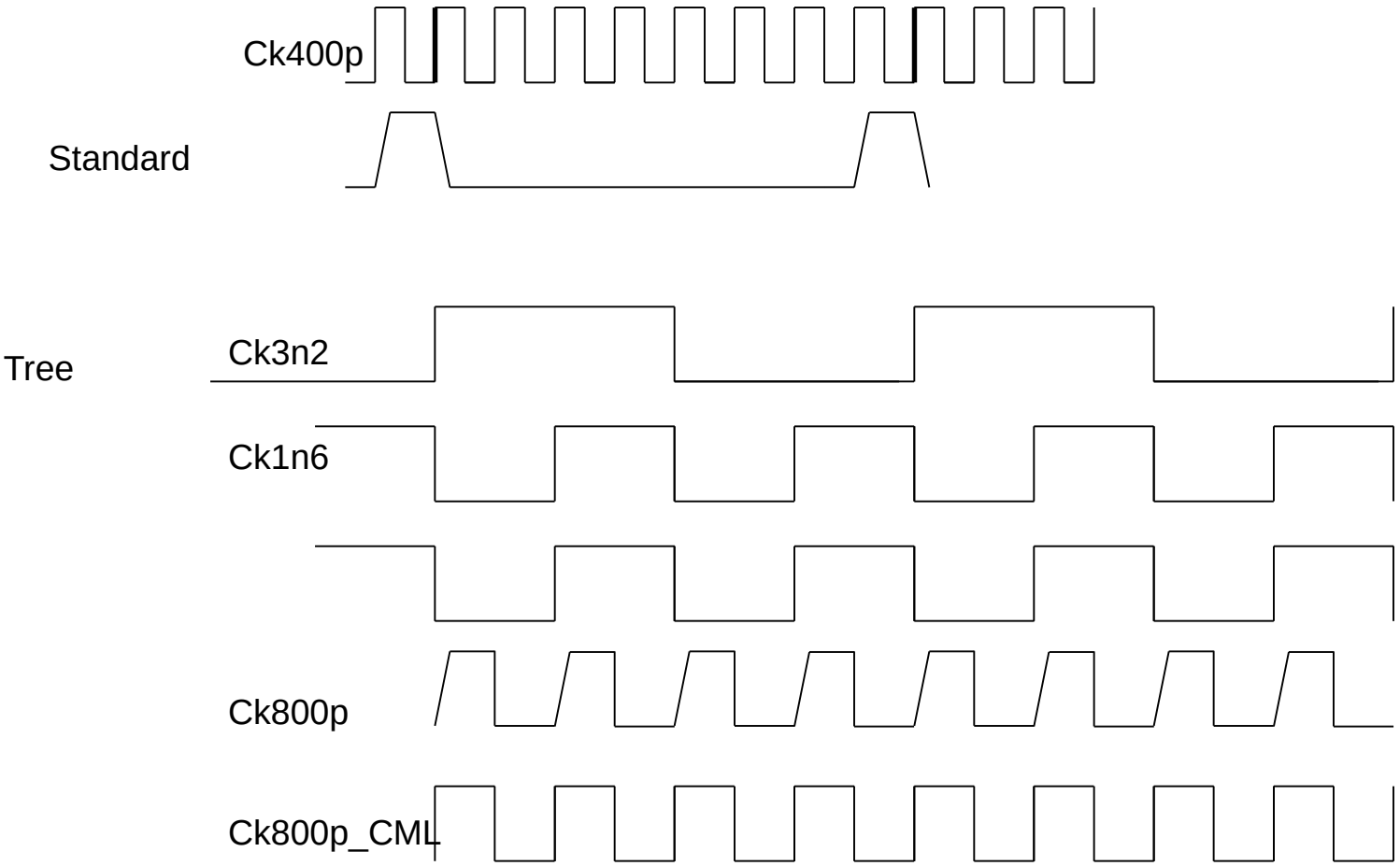
Current-Mode logic



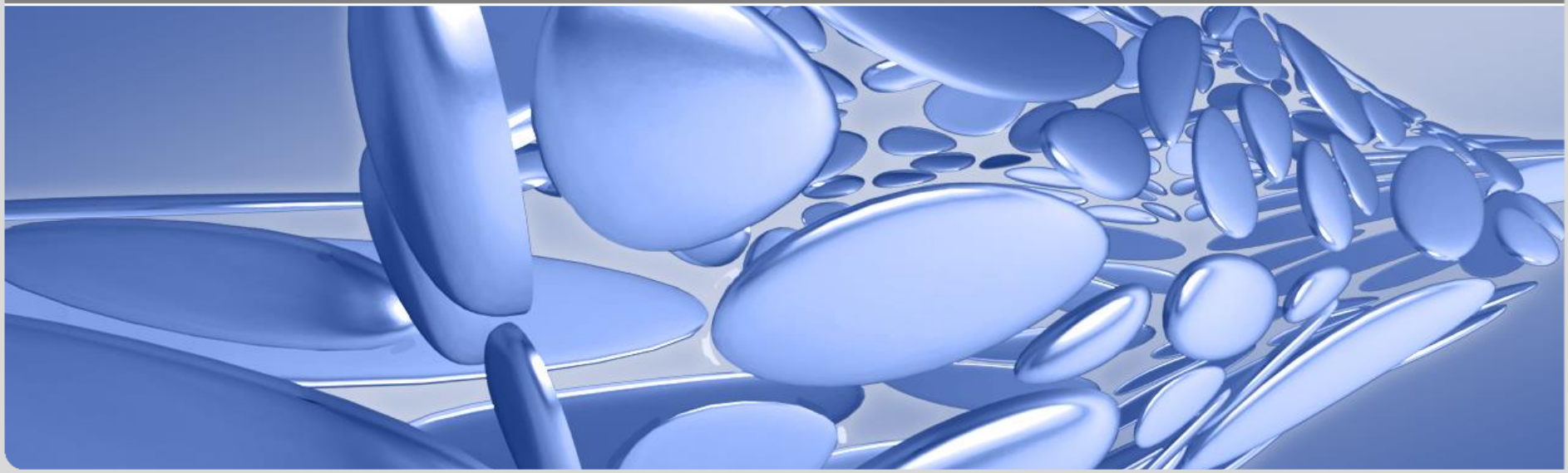



Ck400p

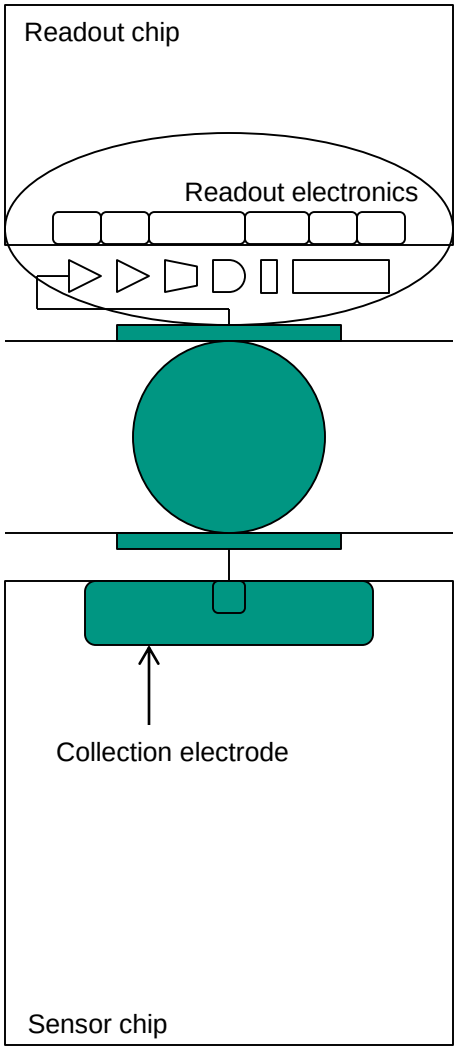

Ck3n2
Ck1n6
Ck800p
Ck800p
Ck800p_CML


Ck400p
Standard
Tree
Ck3n2
Ck1n6
Ck800p
Ck800p_CML

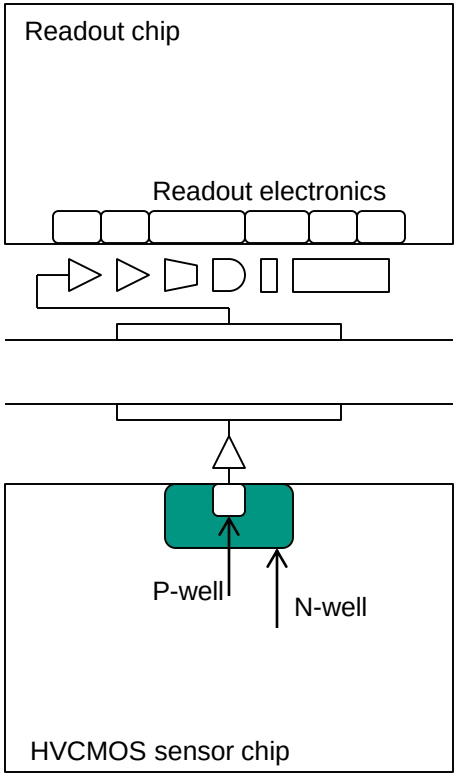
CCPD sensor



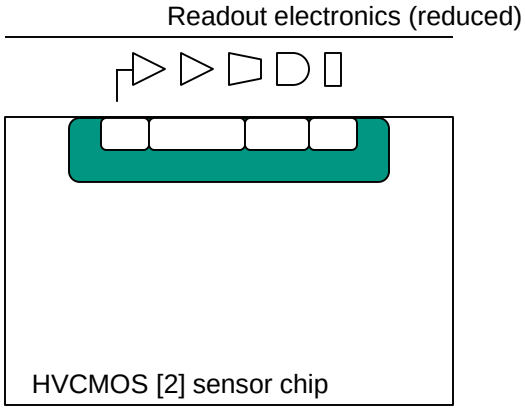
Standard hybrid detector



CCPD [1]

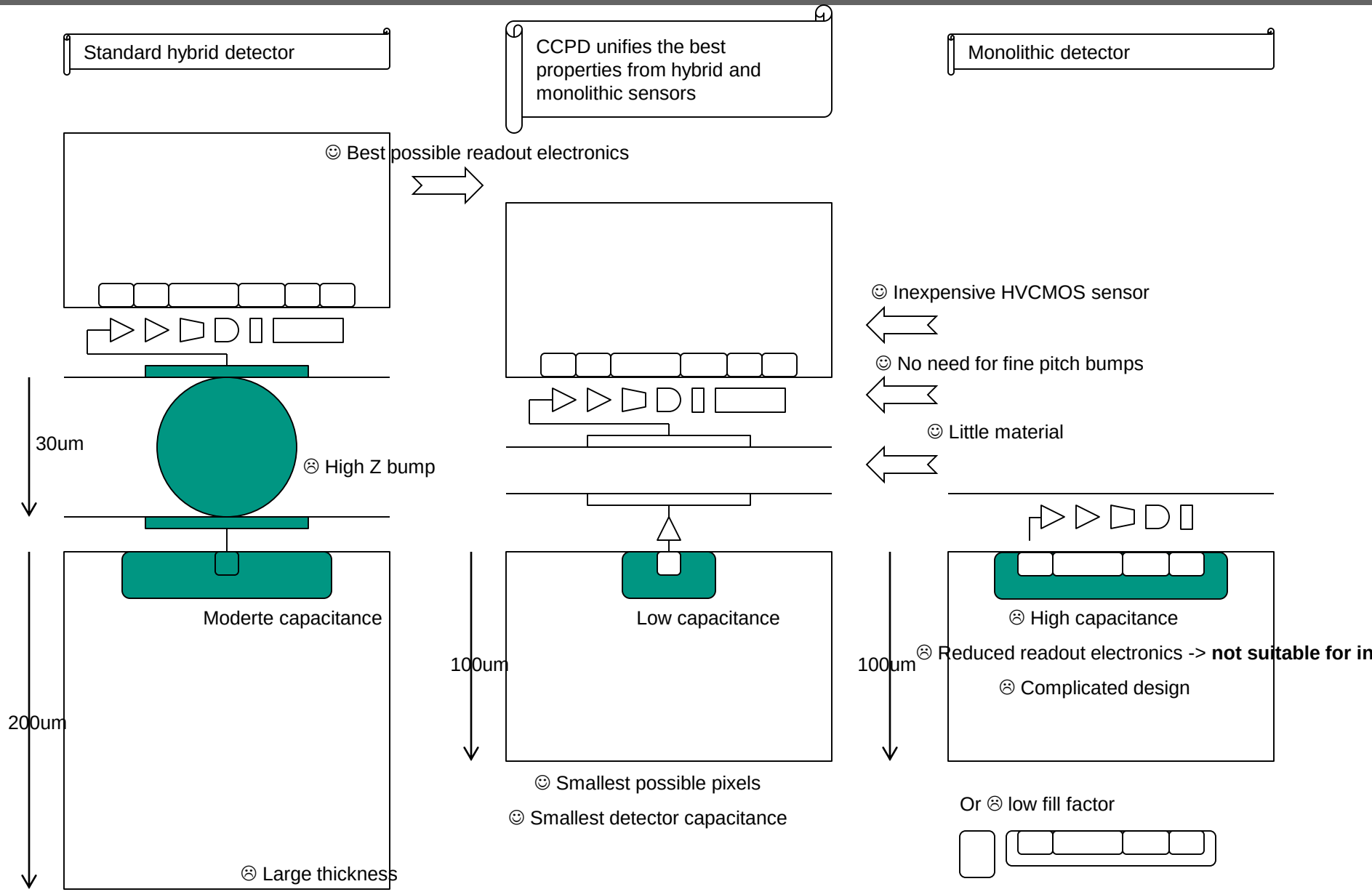


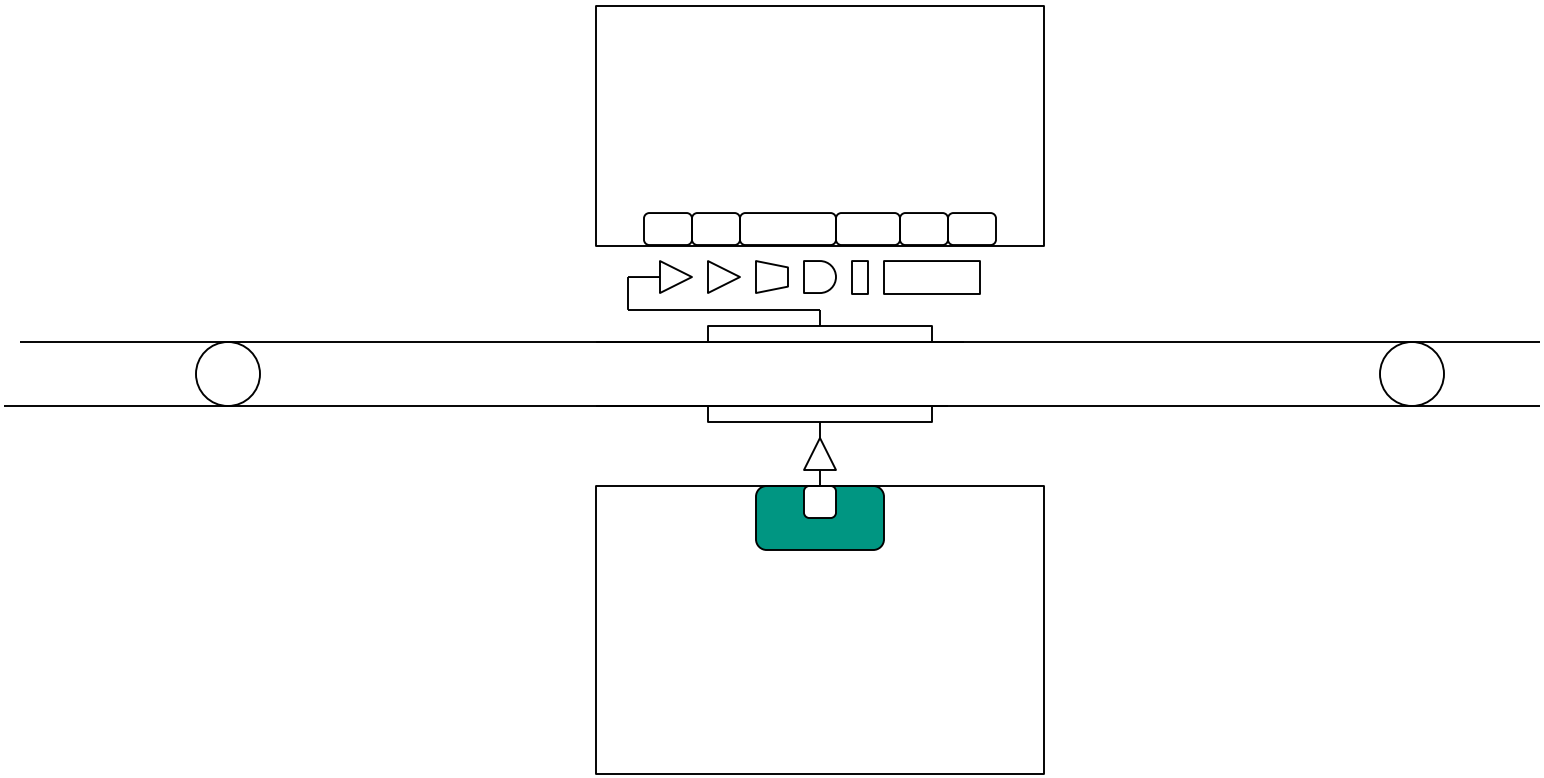
Monolithic detector



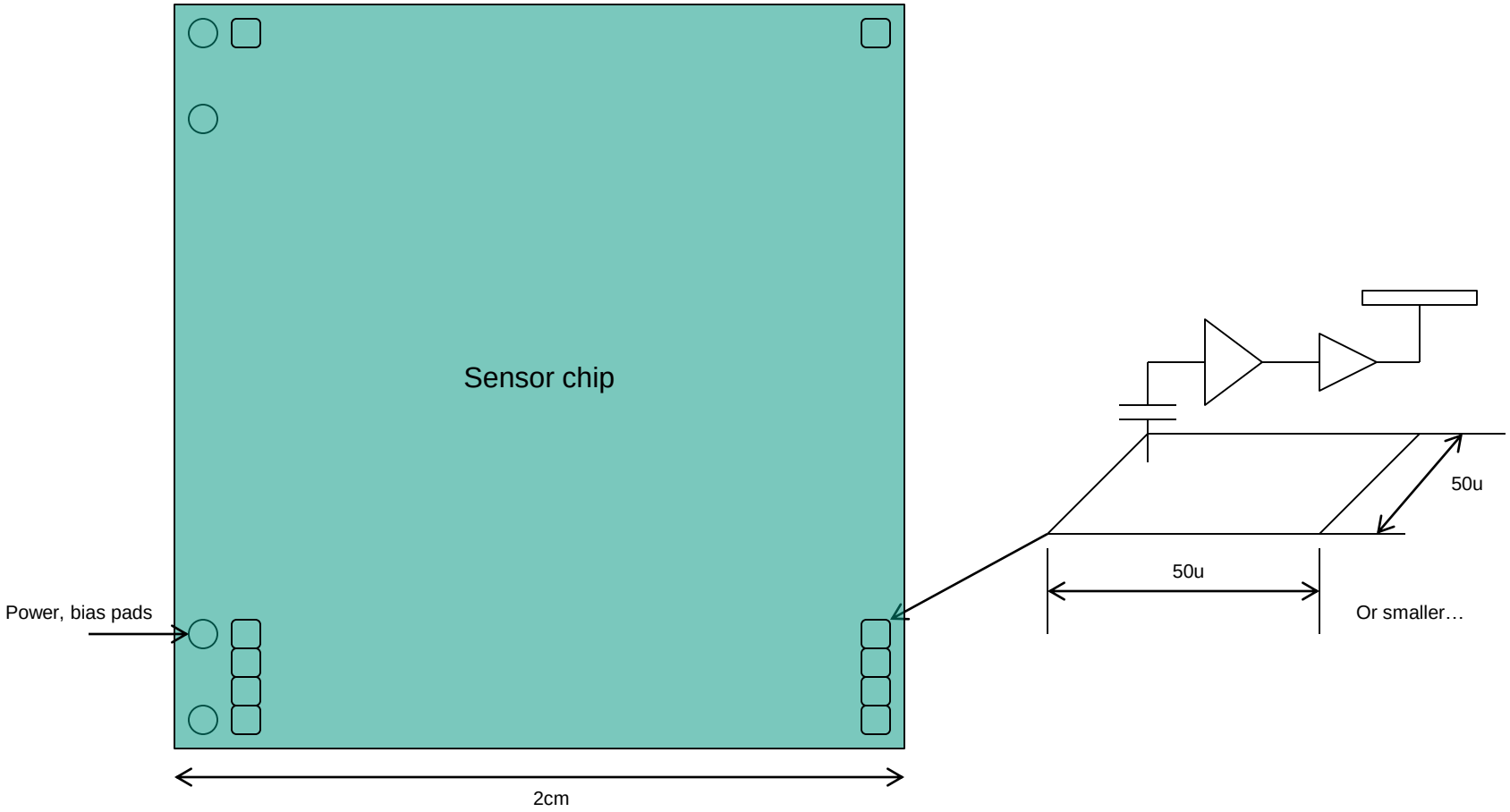
1. I. Peric; "Hybrid Pixel Particle-Detector without Bump Interconnection," IEEE Trans. Nucl. Sci. vol. 56, no. 2, pp. 519-528 (2009).

2. I. Peric; "A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology," Nucl. Inst. Meth. A 582, pp. 876-885 (2007).

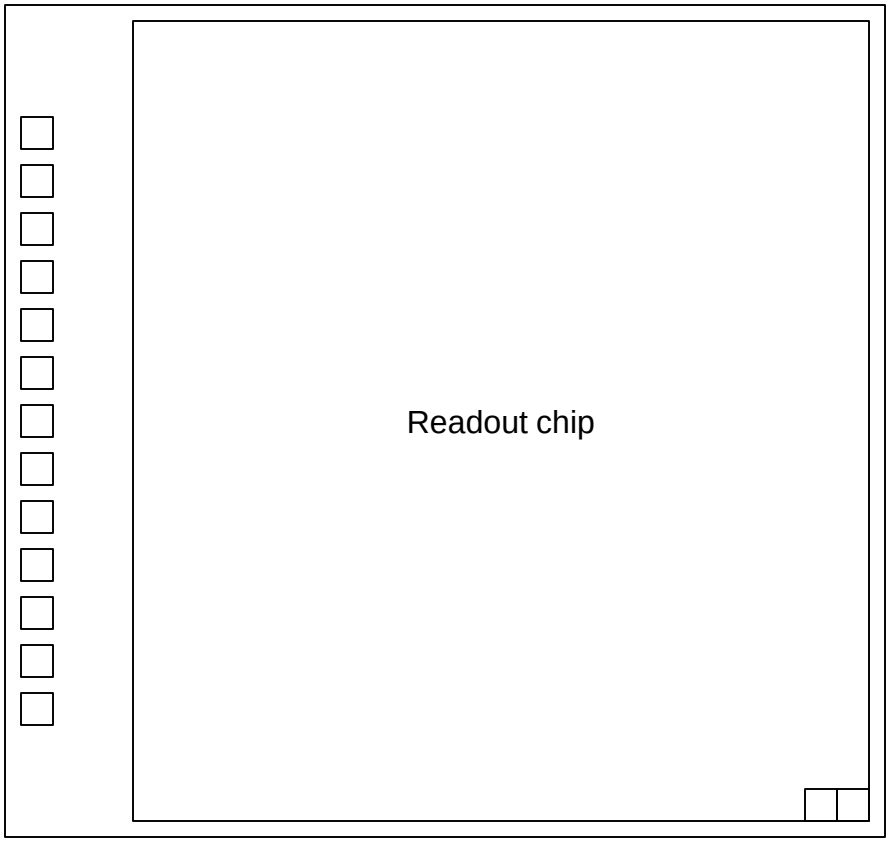

Standard hybrid detector
CCPD unifies the best properties from hybrid and monolithic sensors
Monolithic detector
☺ Best possible readout electronics
☺ Inexpensive HVCMOS sensor
☺ No need for fine pitch bumps
☺ Little material
30um
☹ High Z bump
Moderte capacitance
Low capacitance
☹ High capacitance
100um
100um
200um
☹ Reduced readout electronics -> not suitable for in
☹ Complicated design
☺ Smallest possible pixels
☺ Smallest detector capacitance
Or ☹ low fill factor
☹ Large thickness



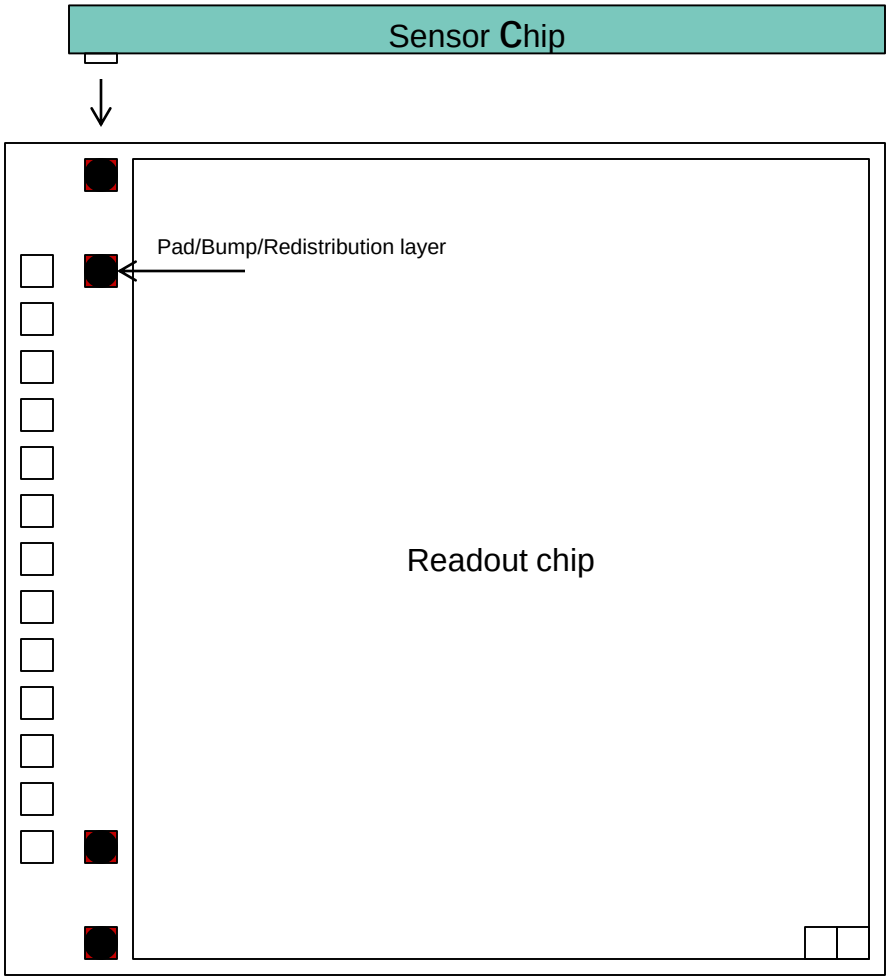
Standard CCPD sensor



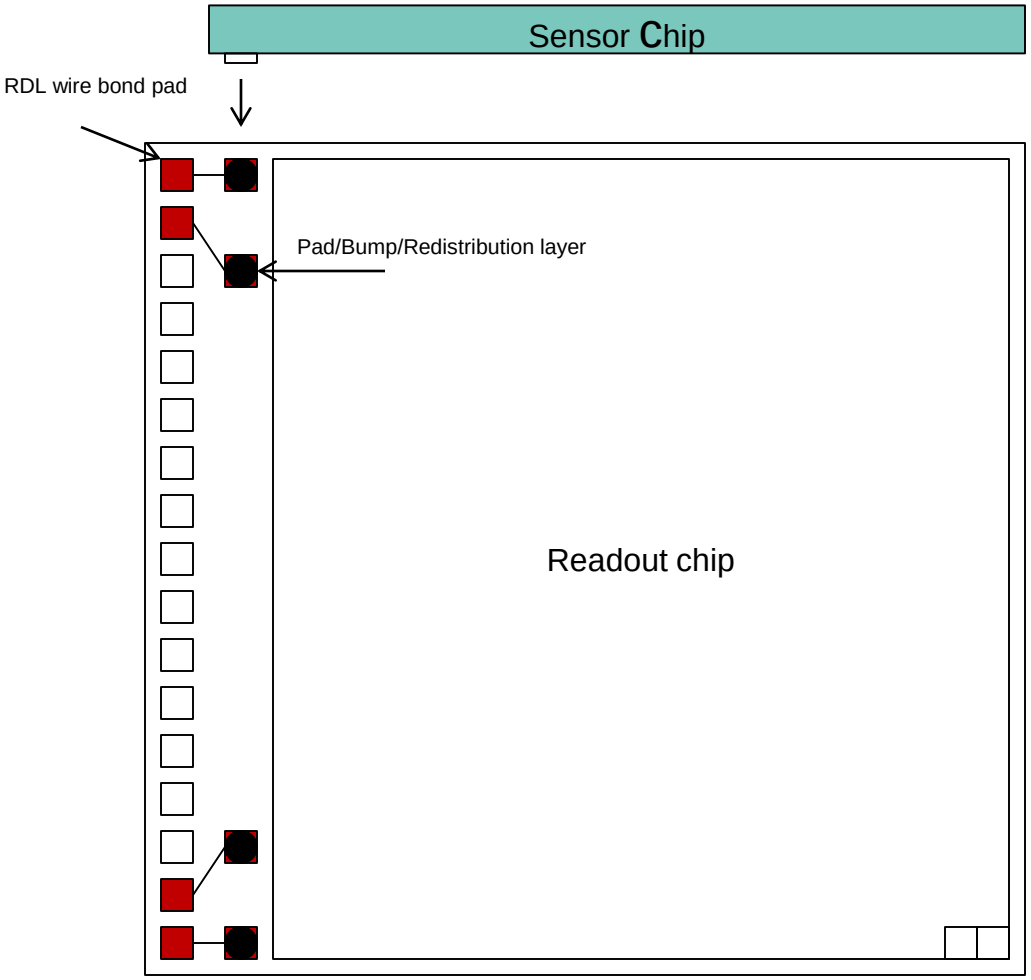
Post-processing of the RD53 chip



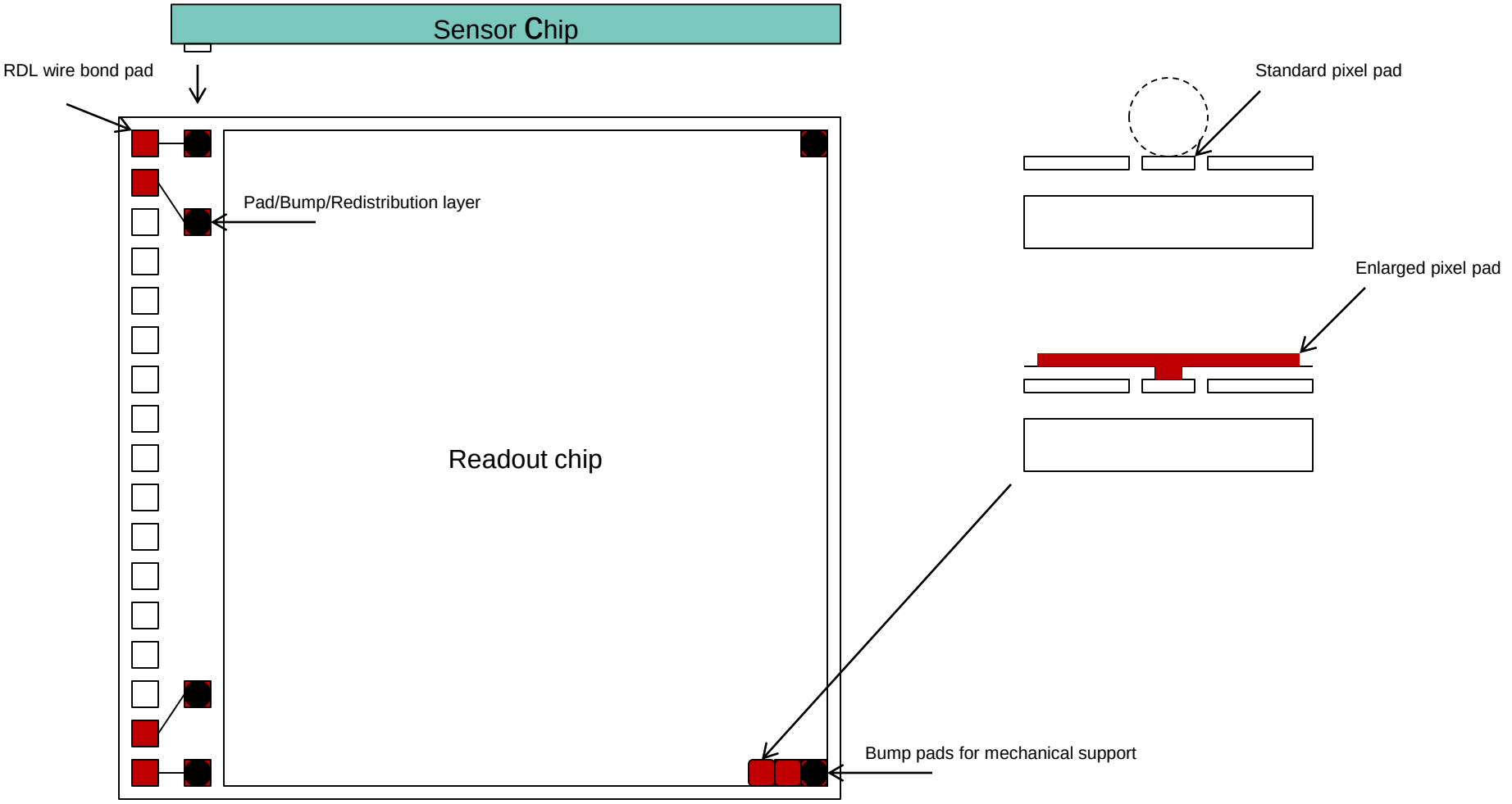
Post-processing of the RD53 chip

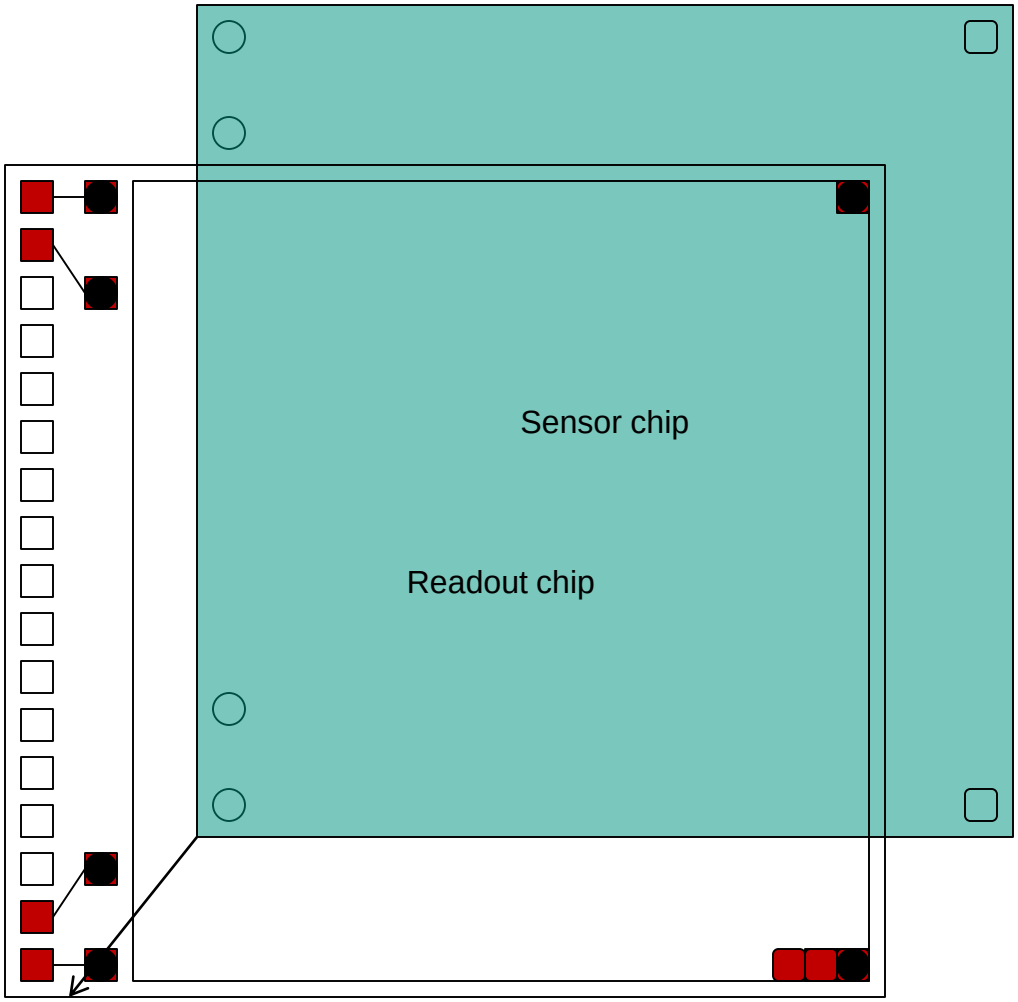


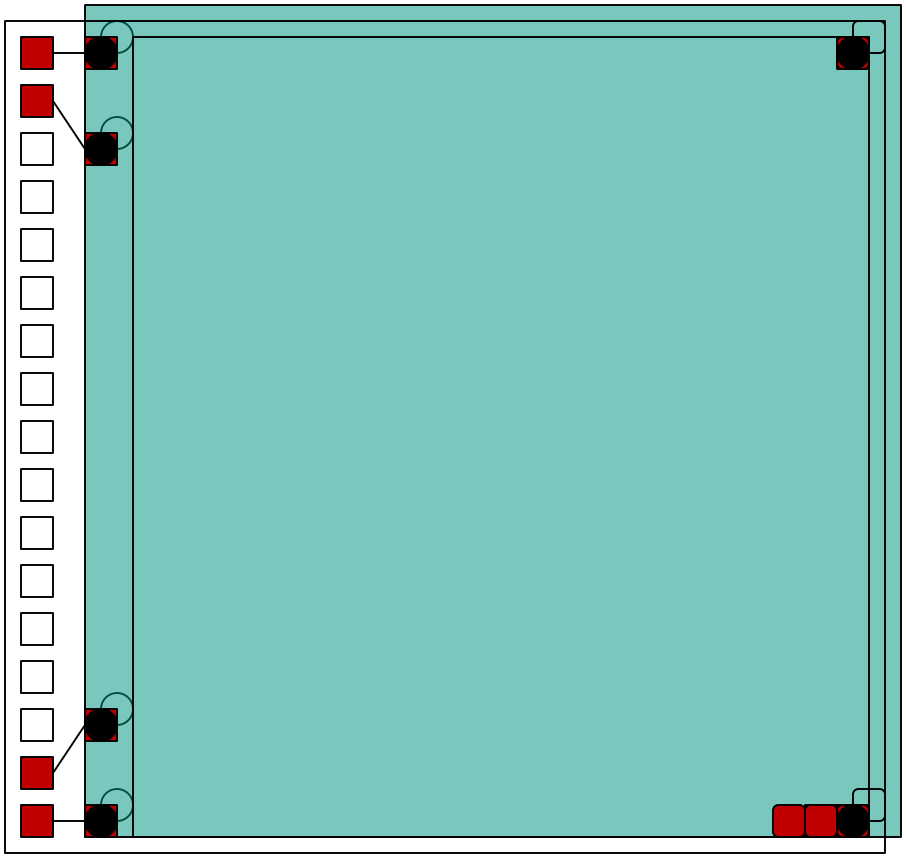
Post-processing of the RD53 chip

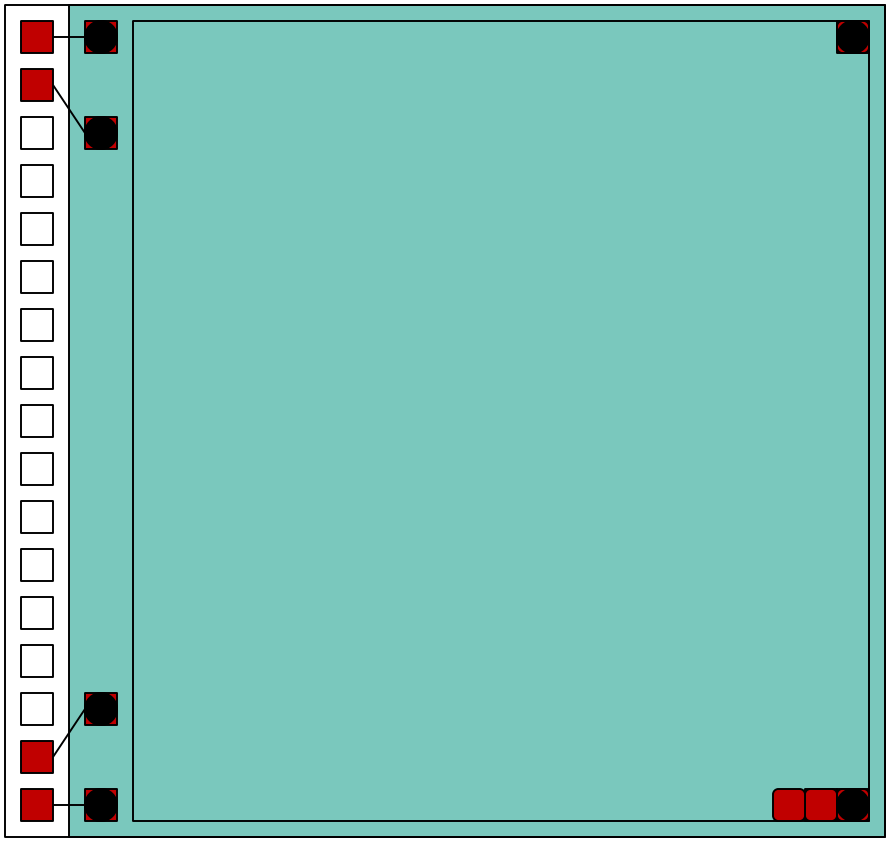


Post-processing of the RD53 chip

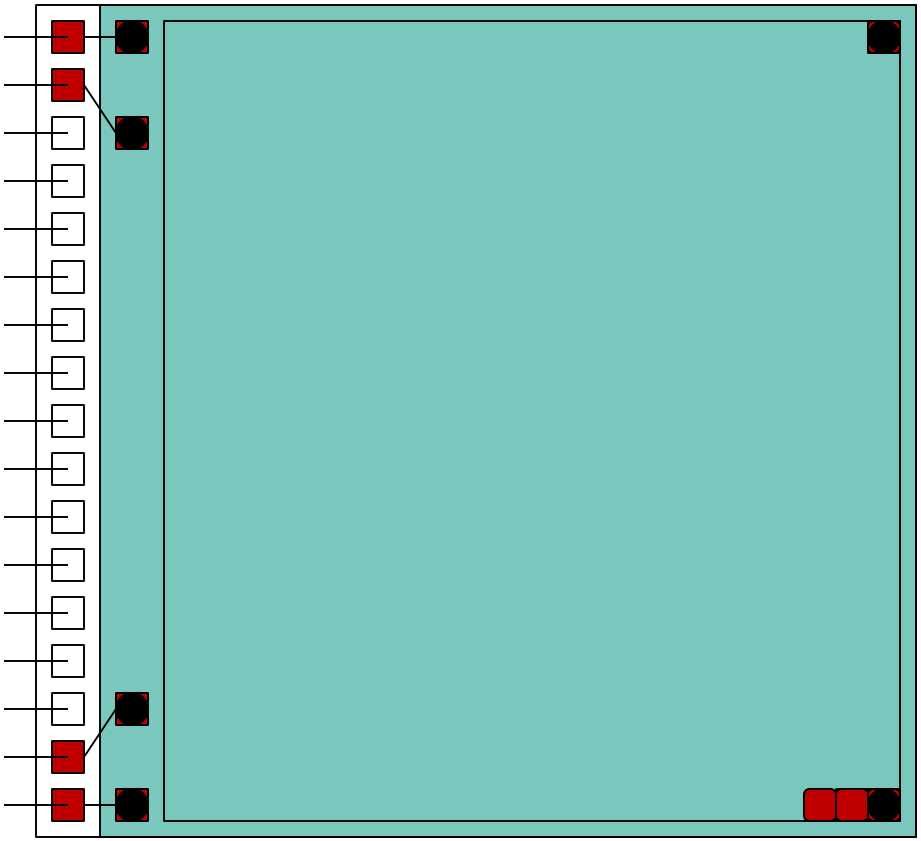



Sensor chip
Readout chip

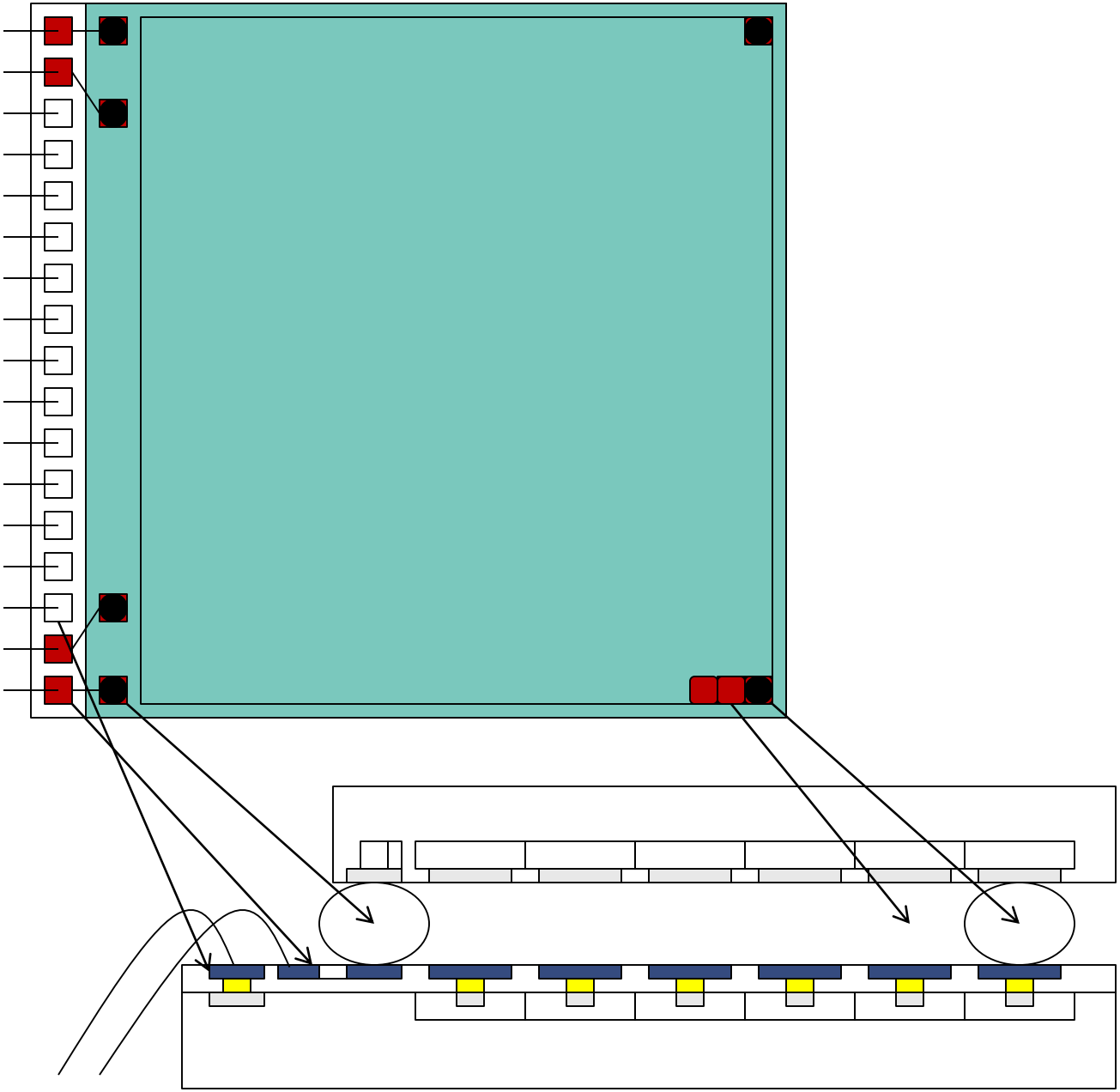


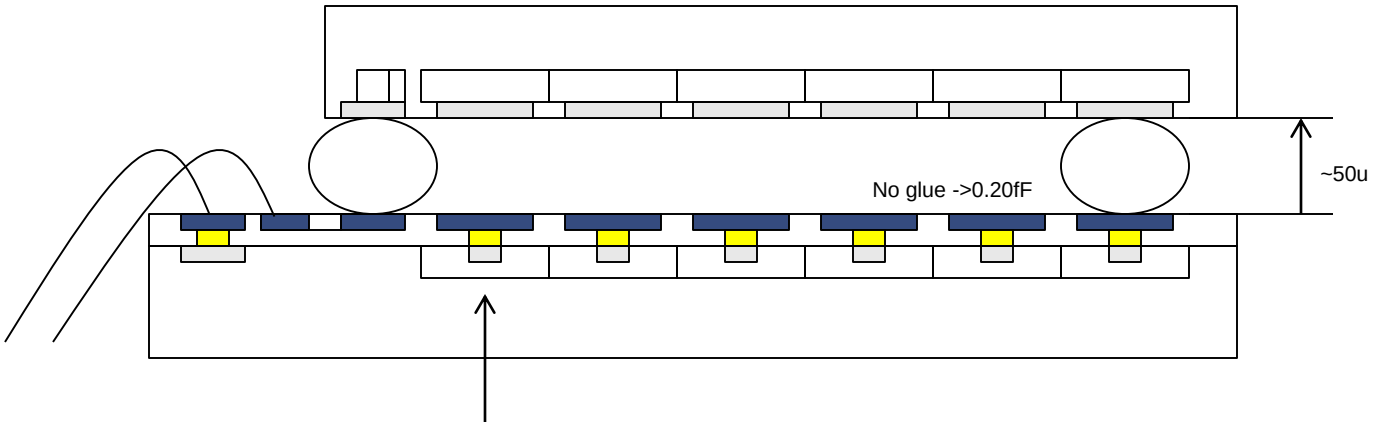


Flip-chip



Flip-chip





Cdet ~20f/2uW/pixel (H18) 4uW (H35)

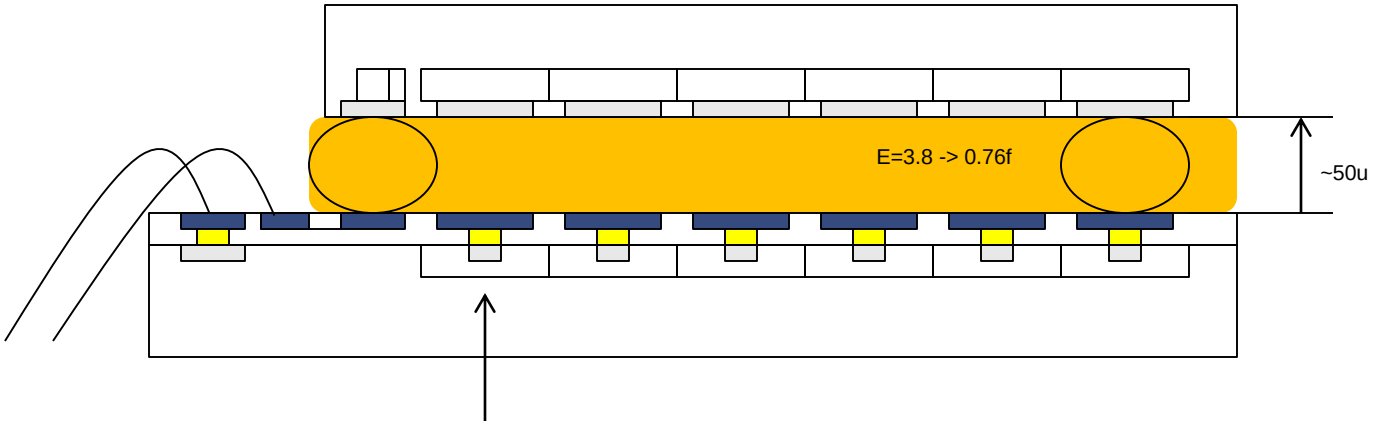
MIP: 200mV(1st amplifier) – 1V (2nd amplifier)

No glue: For signal of 200m V – 240e, for 1V 1200e

The ROC amplifier does not see any detector capacitance, threshold < 1200e is probably possible

Works with 2nd amplifier!

Coupling capacitance



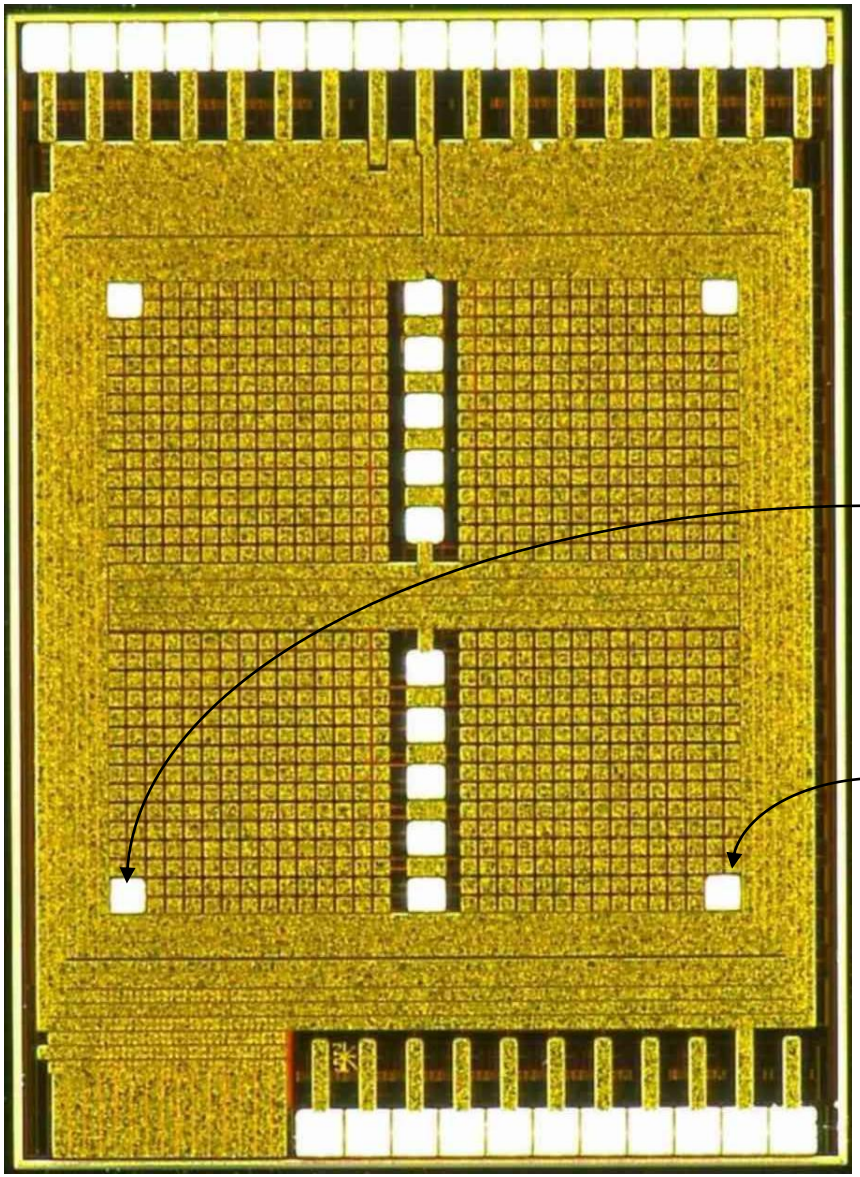
Cdet ~20f/2uW/pixel (H18) 4uW (H35)

MIP: 200mV(1st amplifier) – 1V (2nd amplifier)

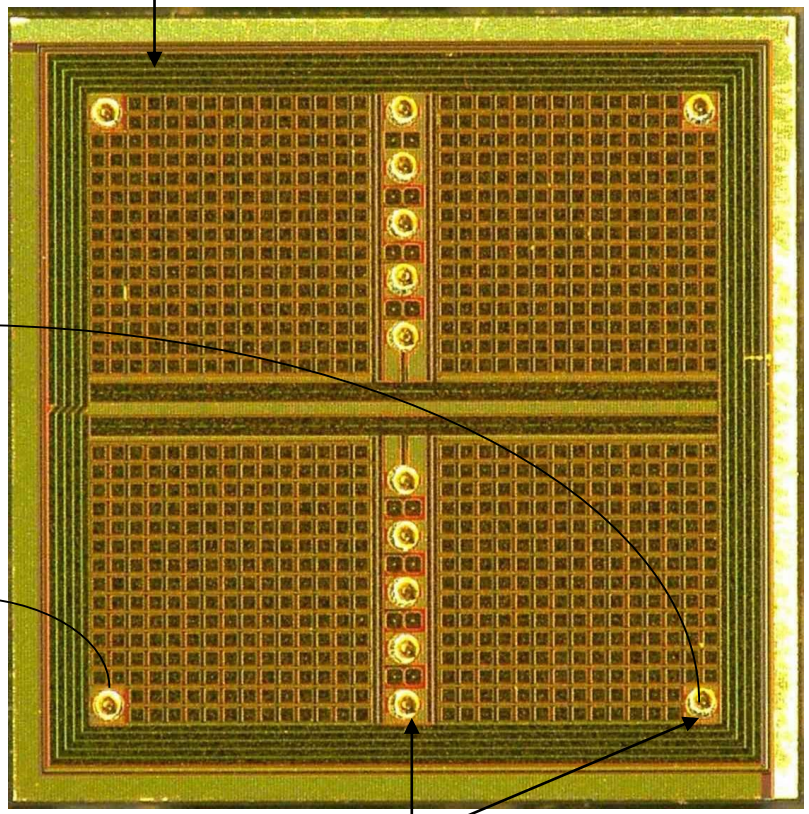
Glue: For signal of 200 mV – 912e

The ROC amplifier does not see any detector capacitance, threshold < 912e is probably possible

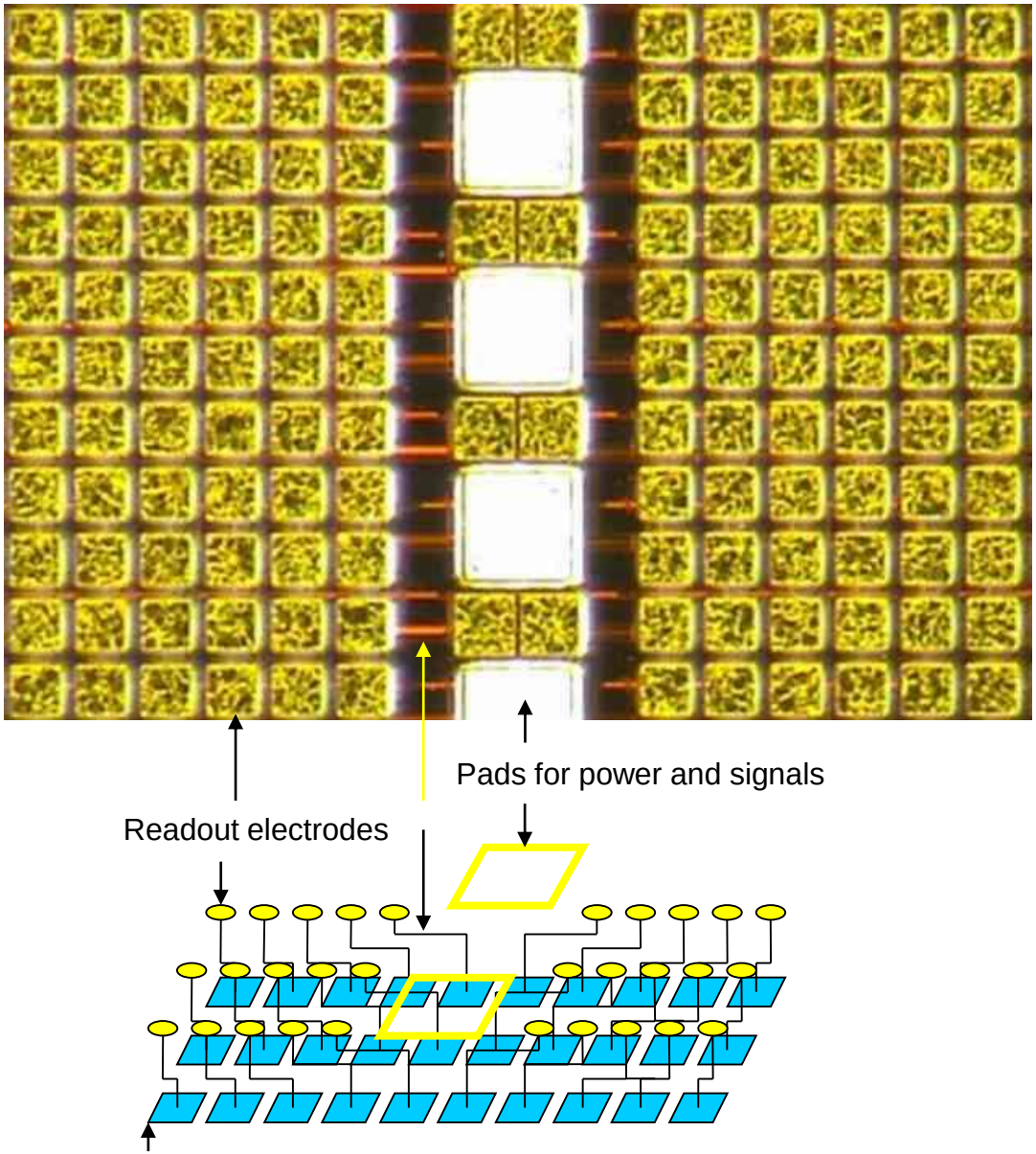
May work also without second amplifier



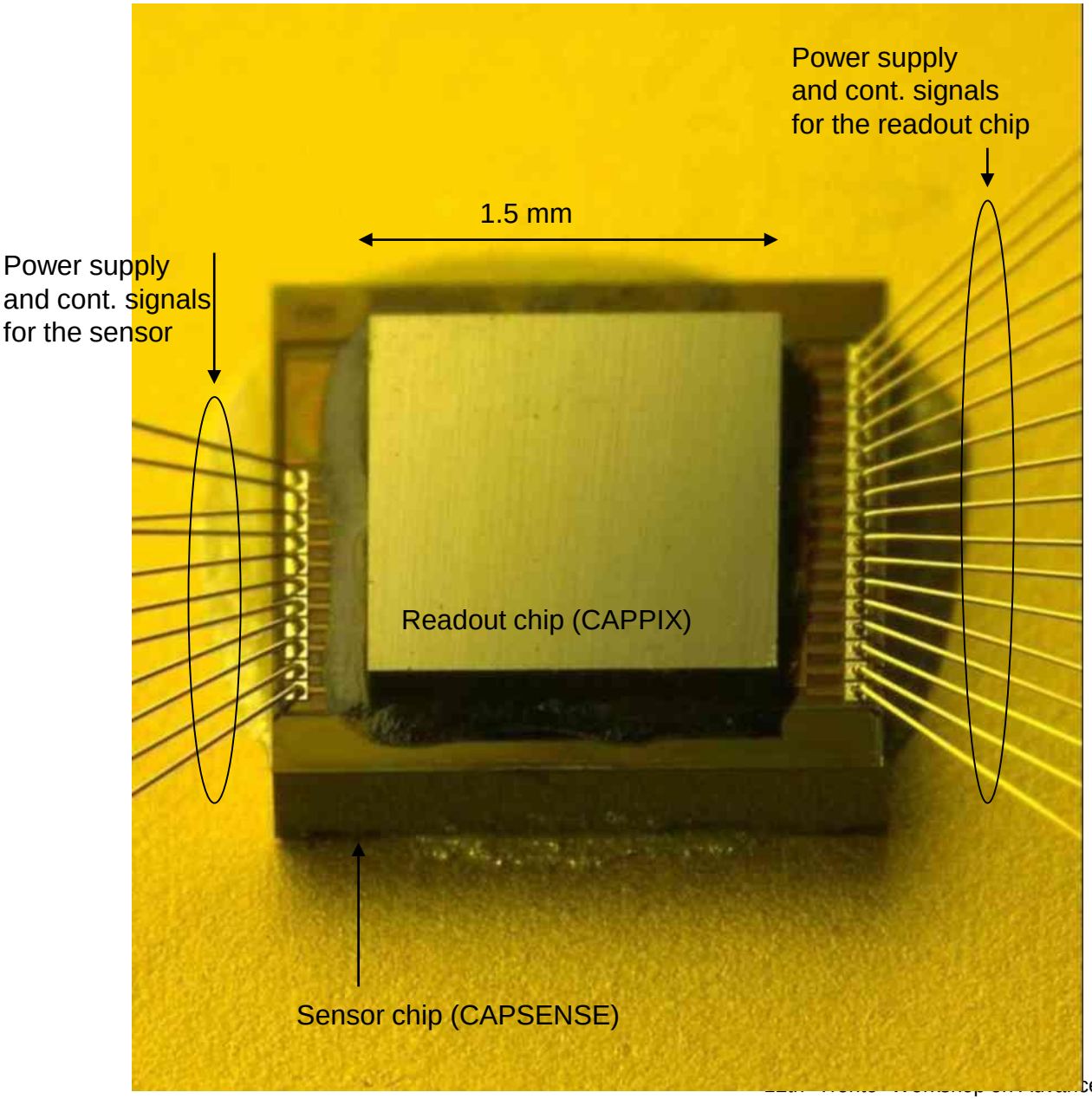
CAPSENSE

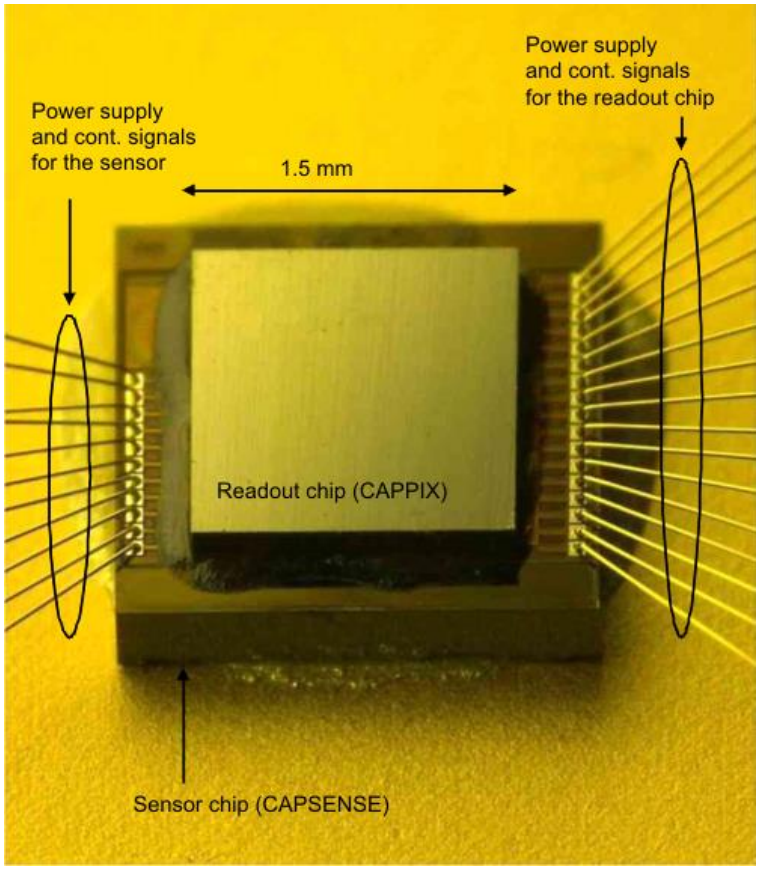


I. Peric, C. Kreidl, P. Fischer; "Hybrid pixel detector based on capacitive chip to chip signal transmission," Nucl. Inst. Meth. A 617, Issues 1-3, pp. 576-581 (2010).

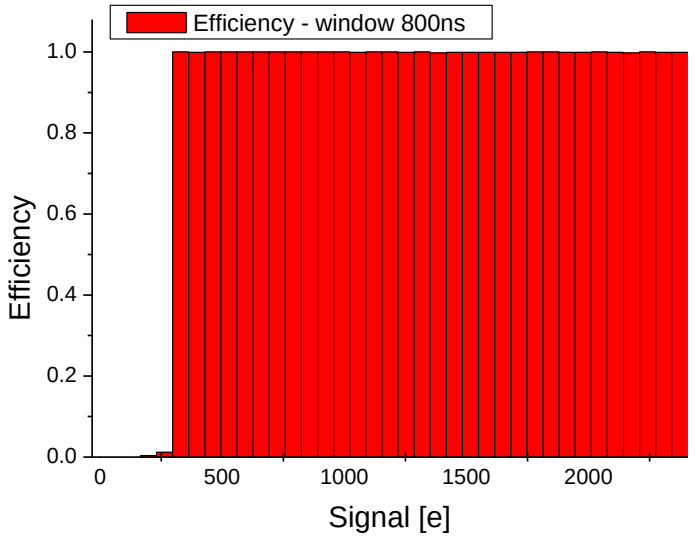

Pads for power and signals
Readout electrodes
Sensor pixels

First prototype



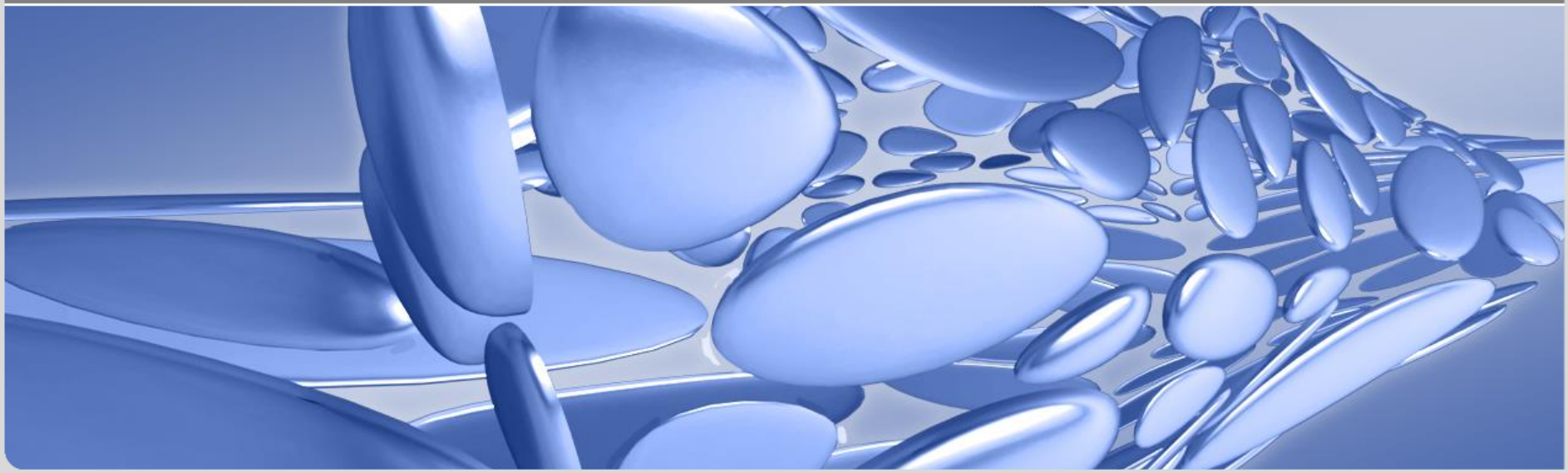


Pixel matrix efficiency:
Detection of signals > 350e possible
MIP signal ~ 1800 e

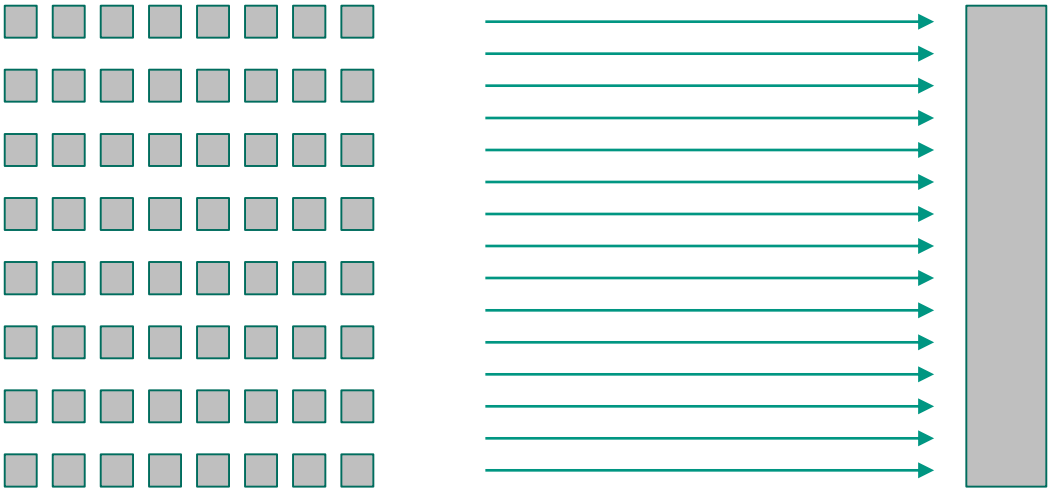


CAPPIX/CAPSENSE edgeless CCPD
55x55 µm pixel size

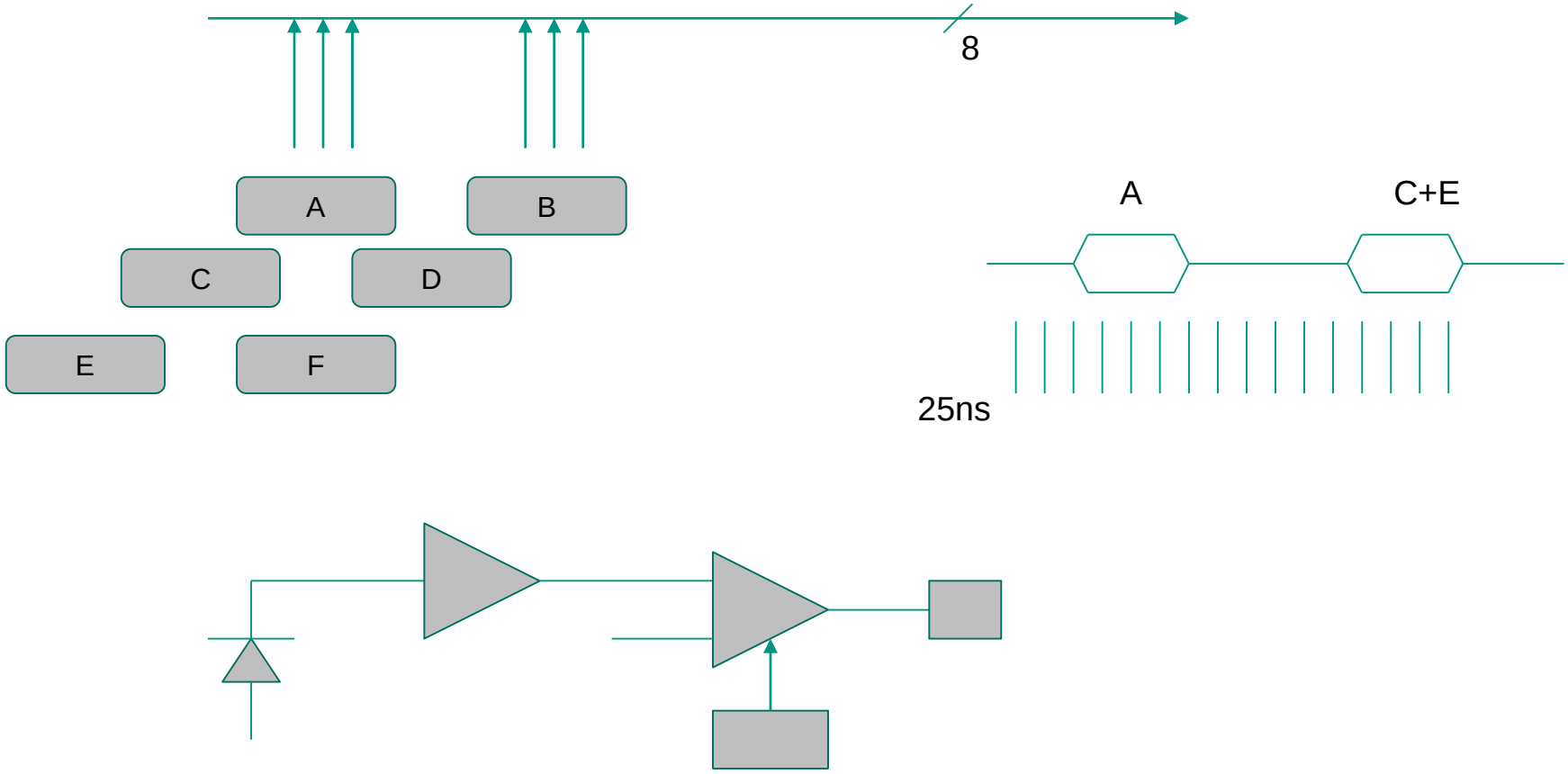
aH18 Run – sensor types



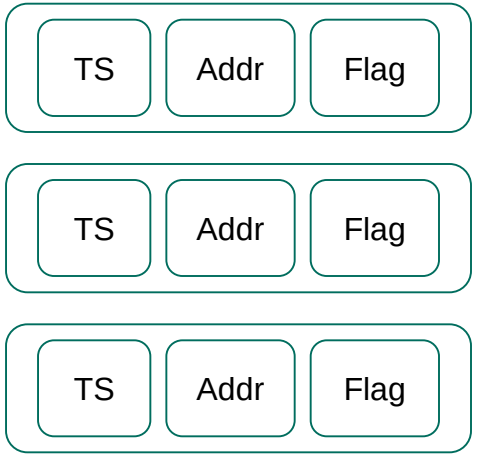
- M Matrix
- Triggered readout, digital pixels
- 50um x 60um

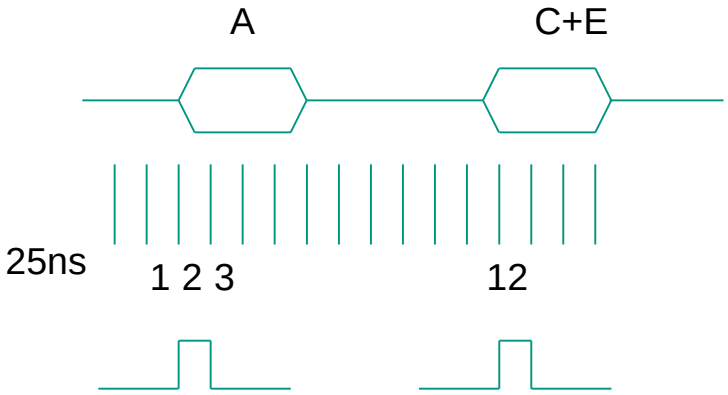


- Monolithic Readout

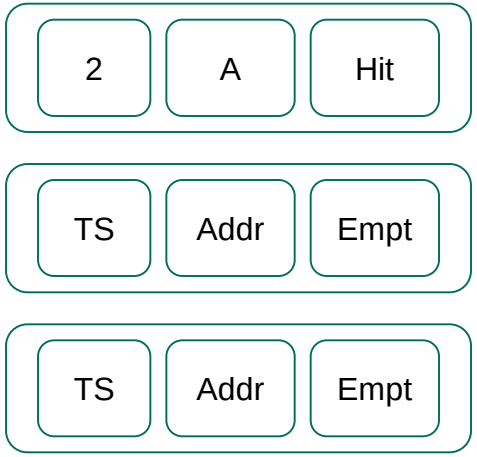


- Monolithic Readout

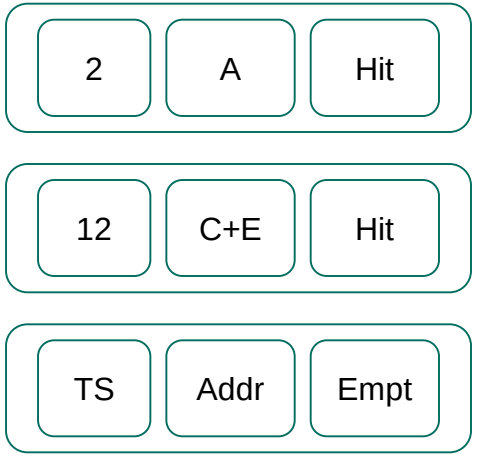




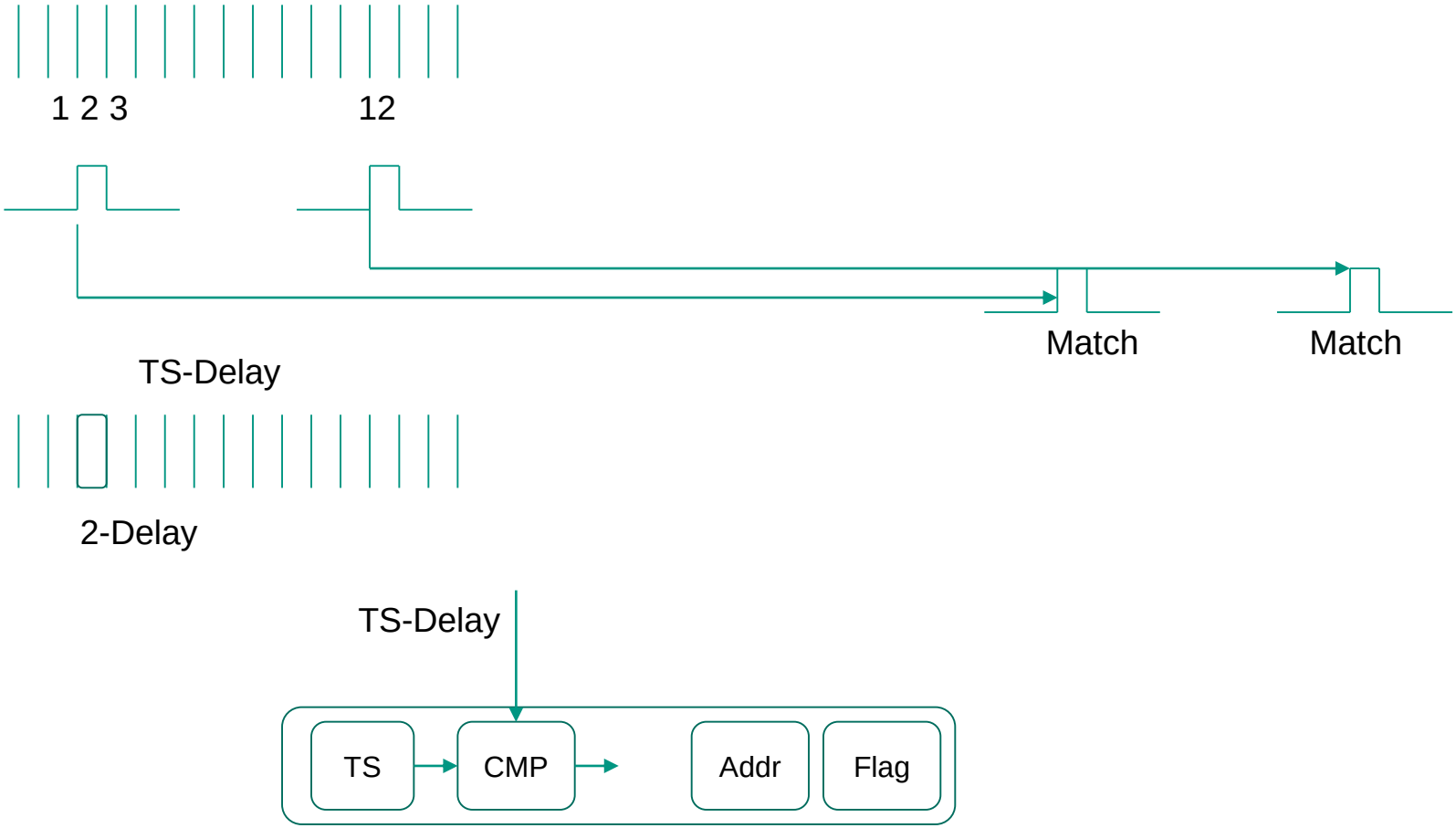
- Monolithic Readout



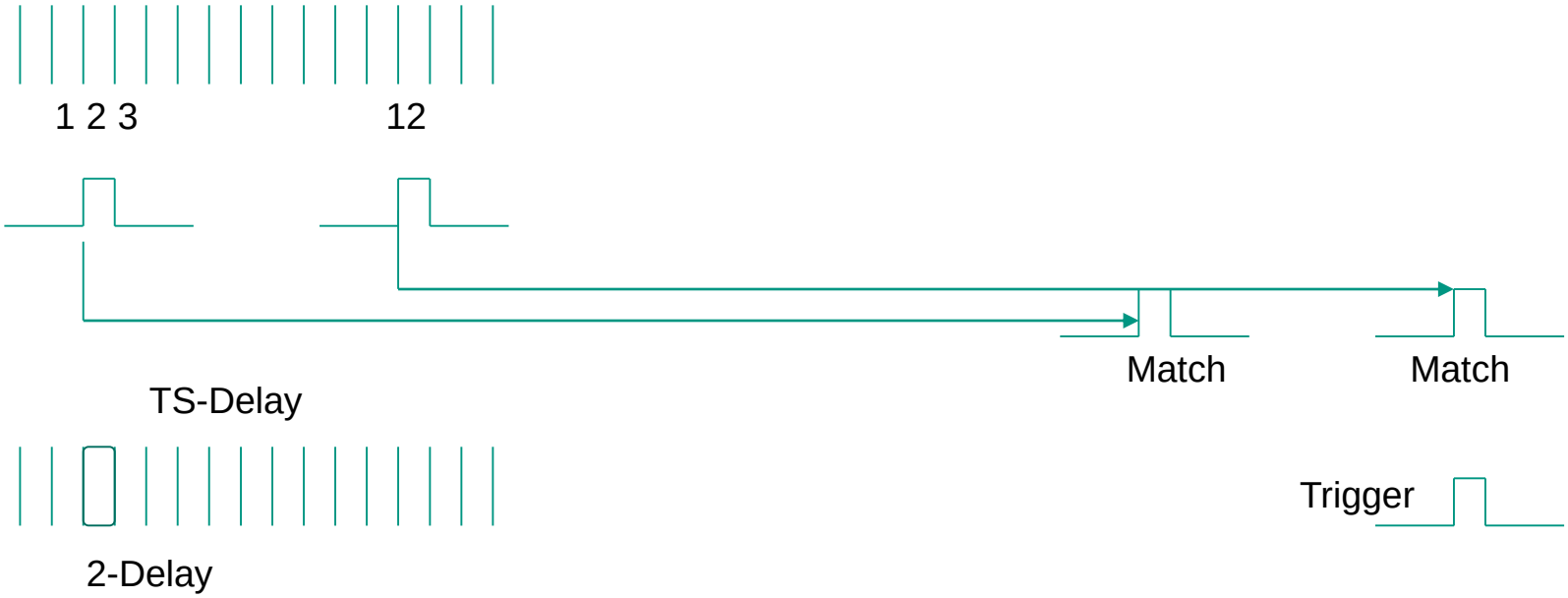
- Monolithic Readout

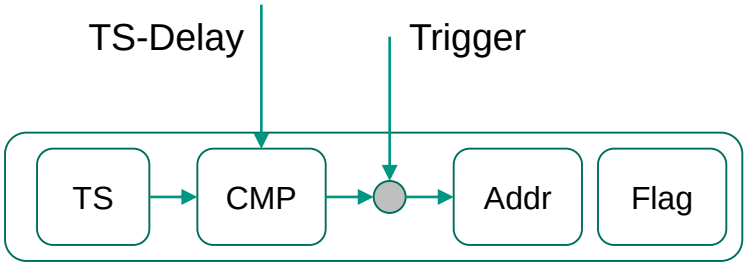


- Monolithic Readout

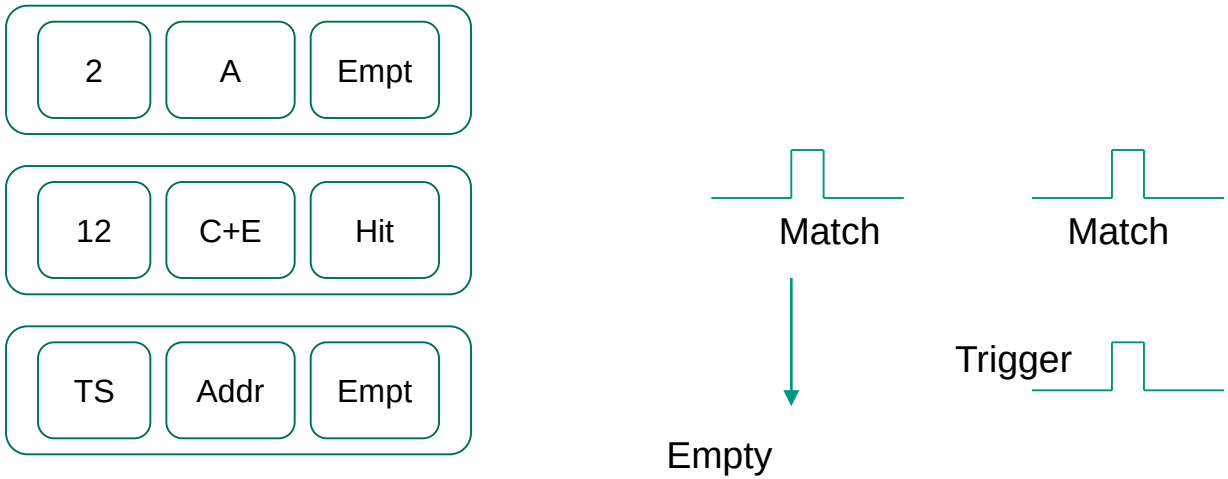


- Monolithic Readout

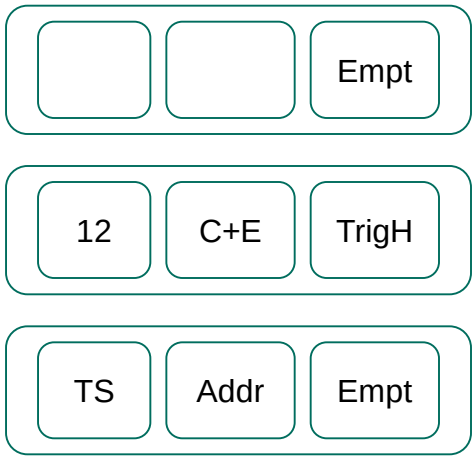


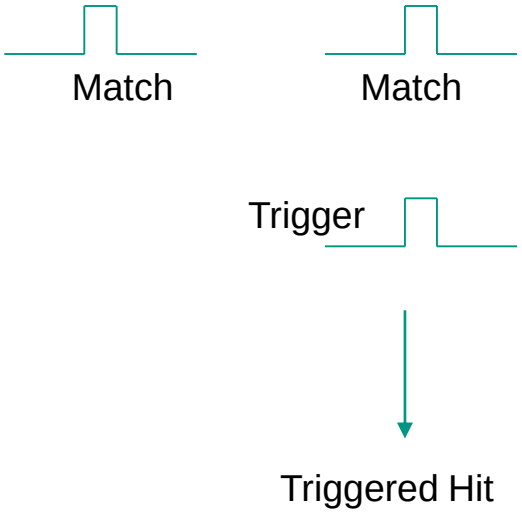


- Monolithic Readout

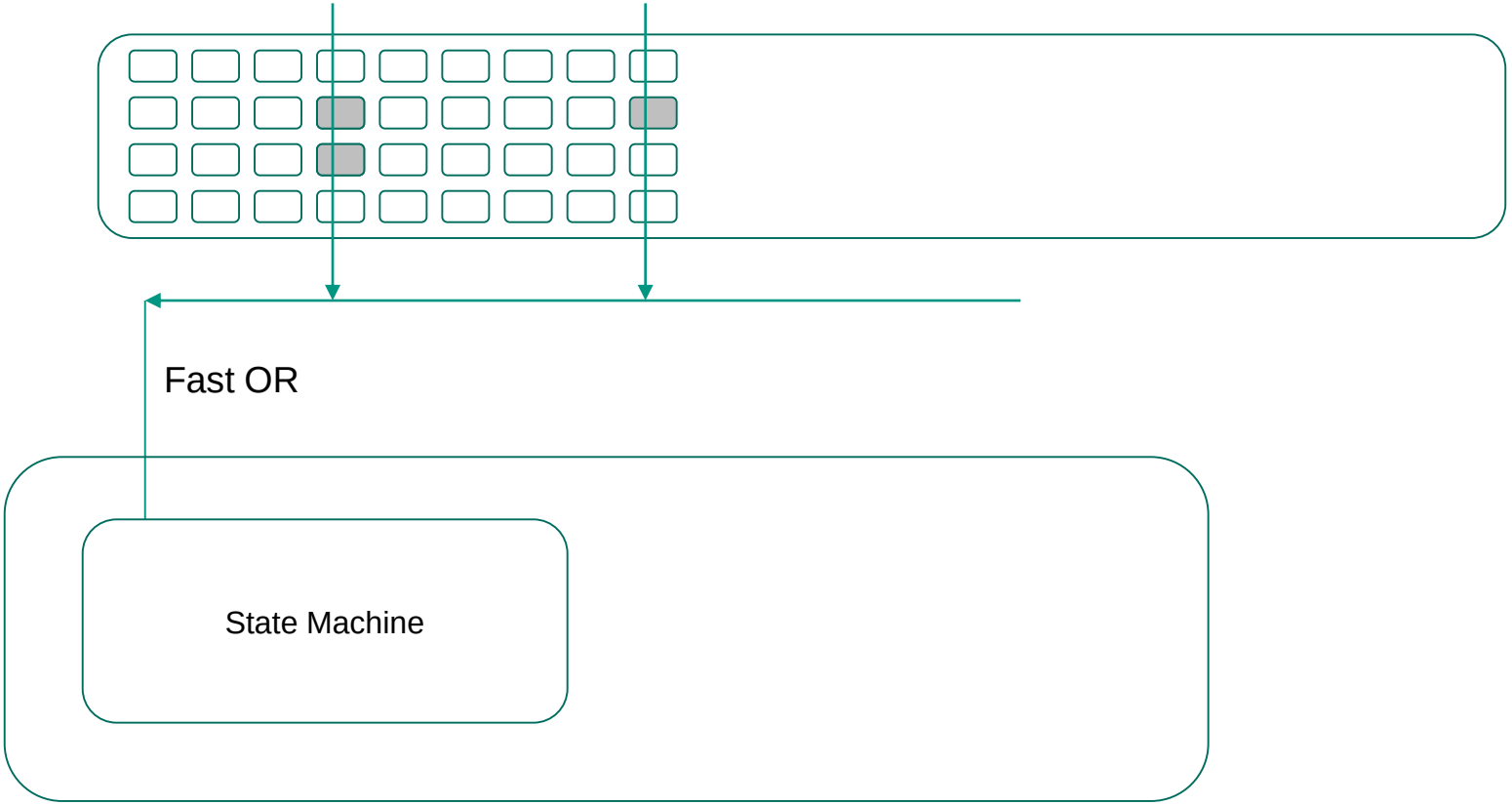


- Monolithic Readout

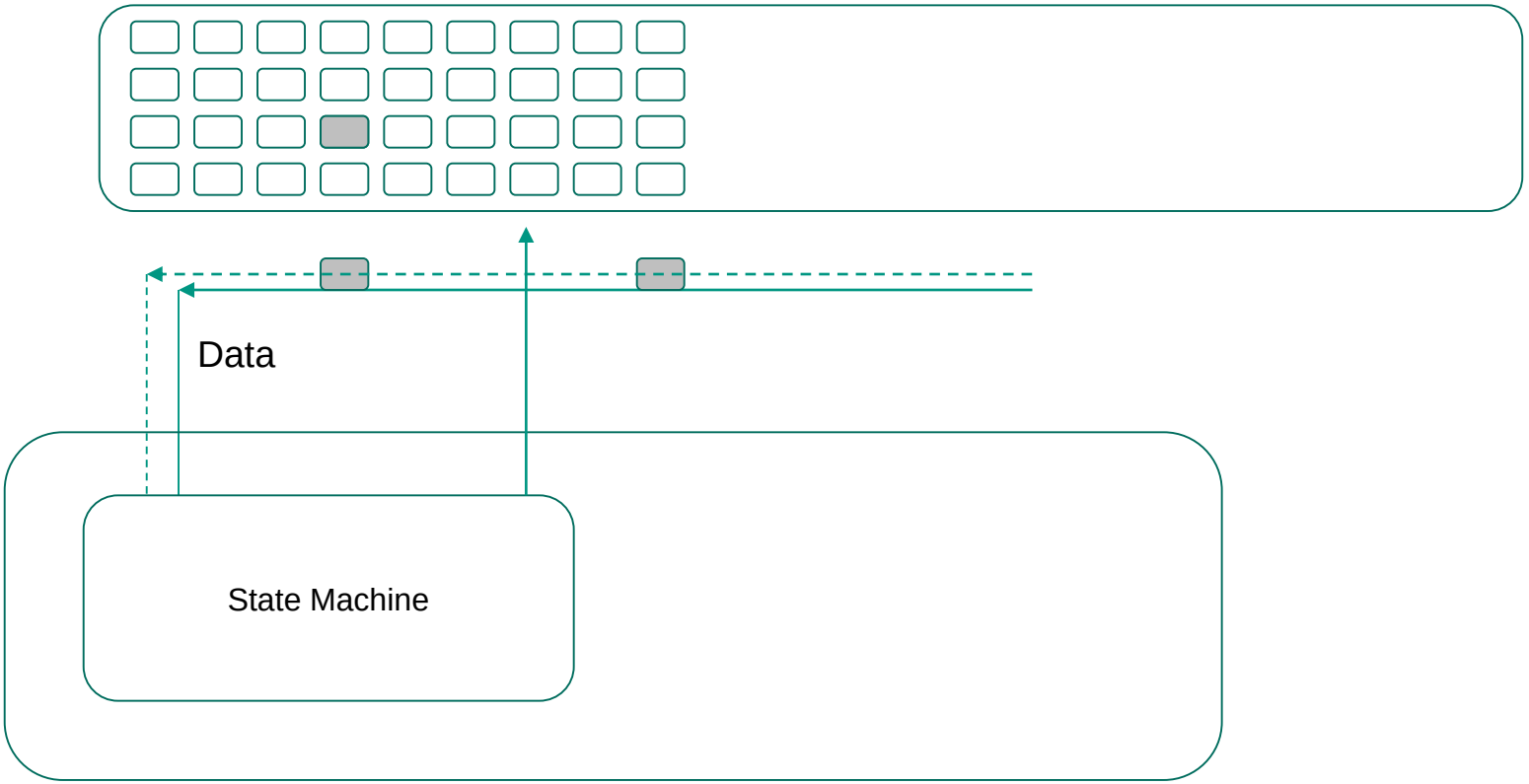




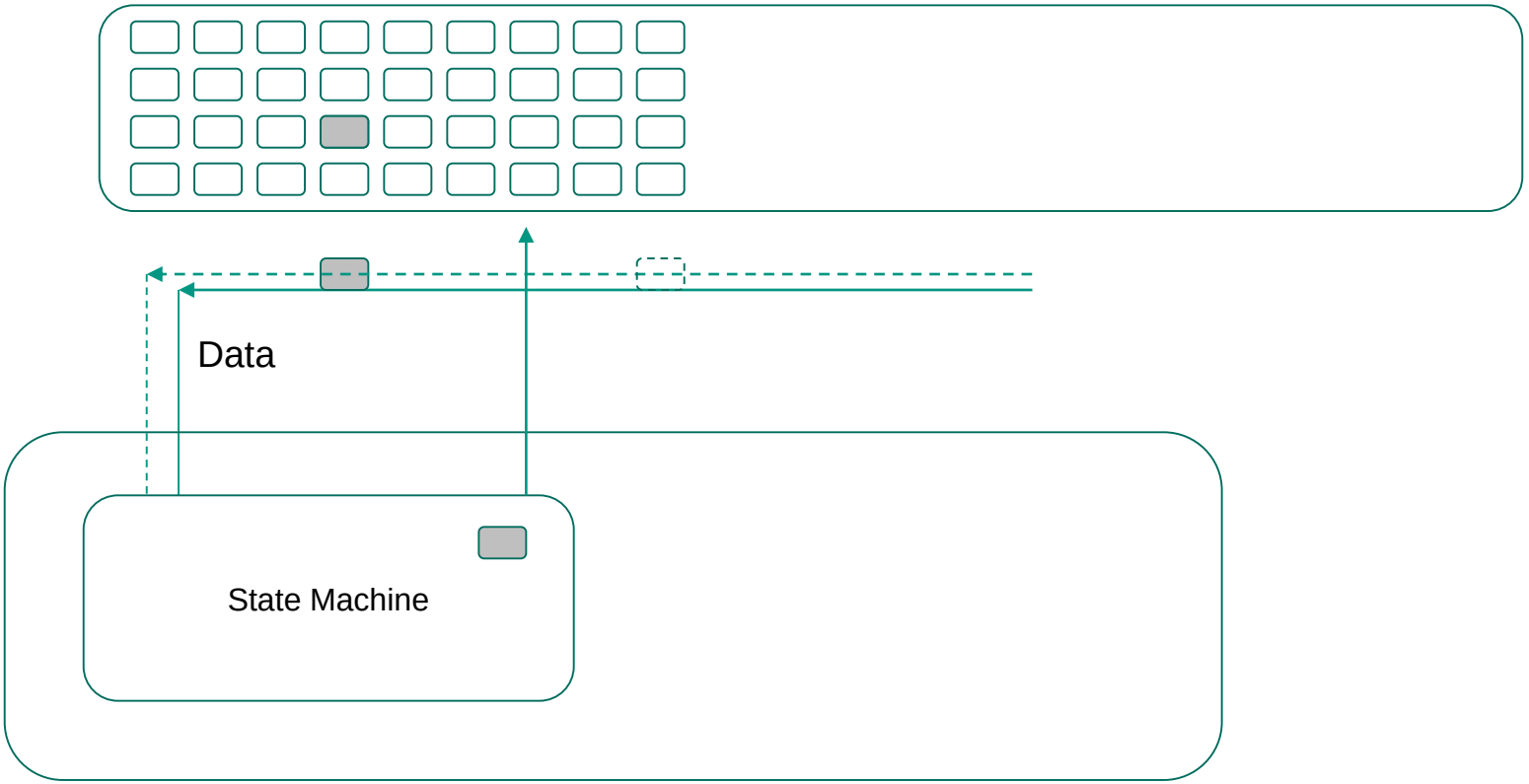
- Monolithic Readout



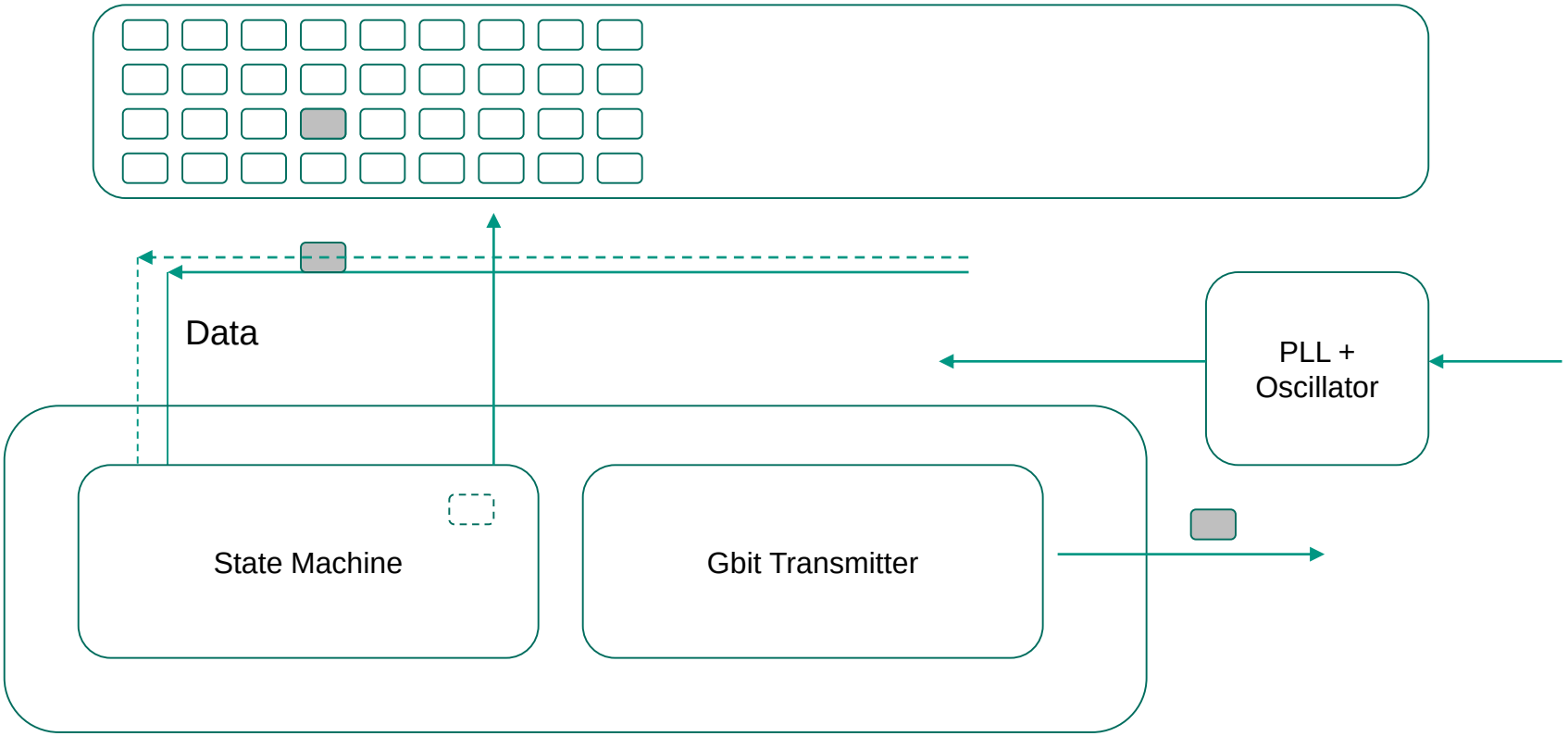
- Monolithic Readout



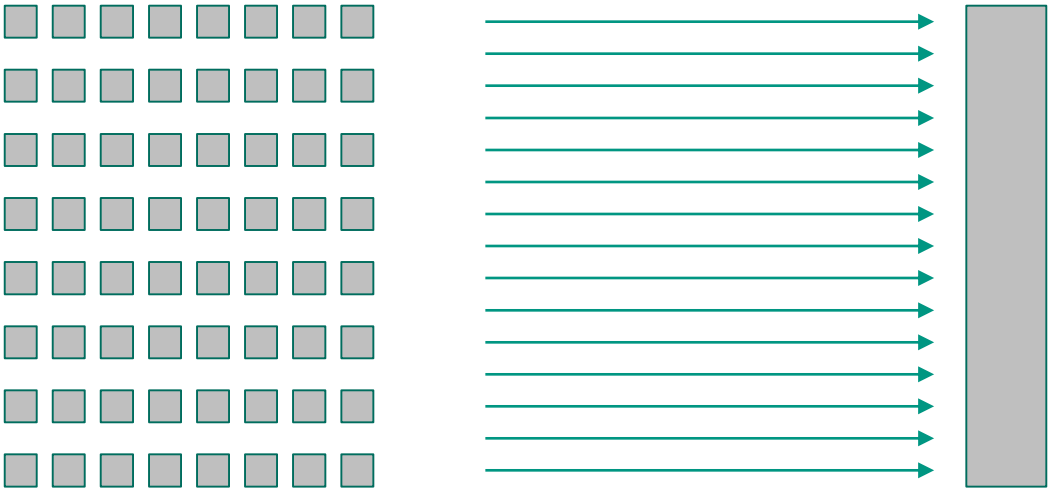
- Monolithic Readout



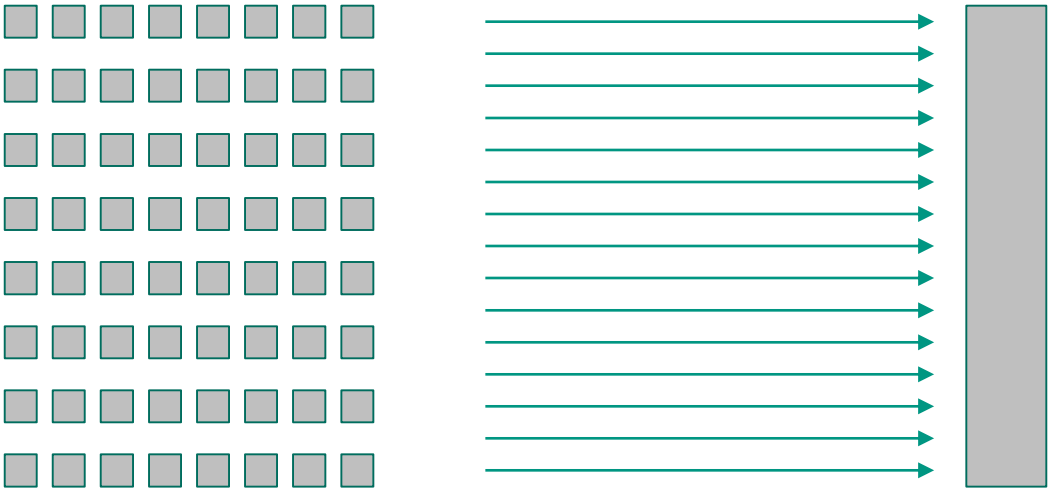
- Monolithic Readout

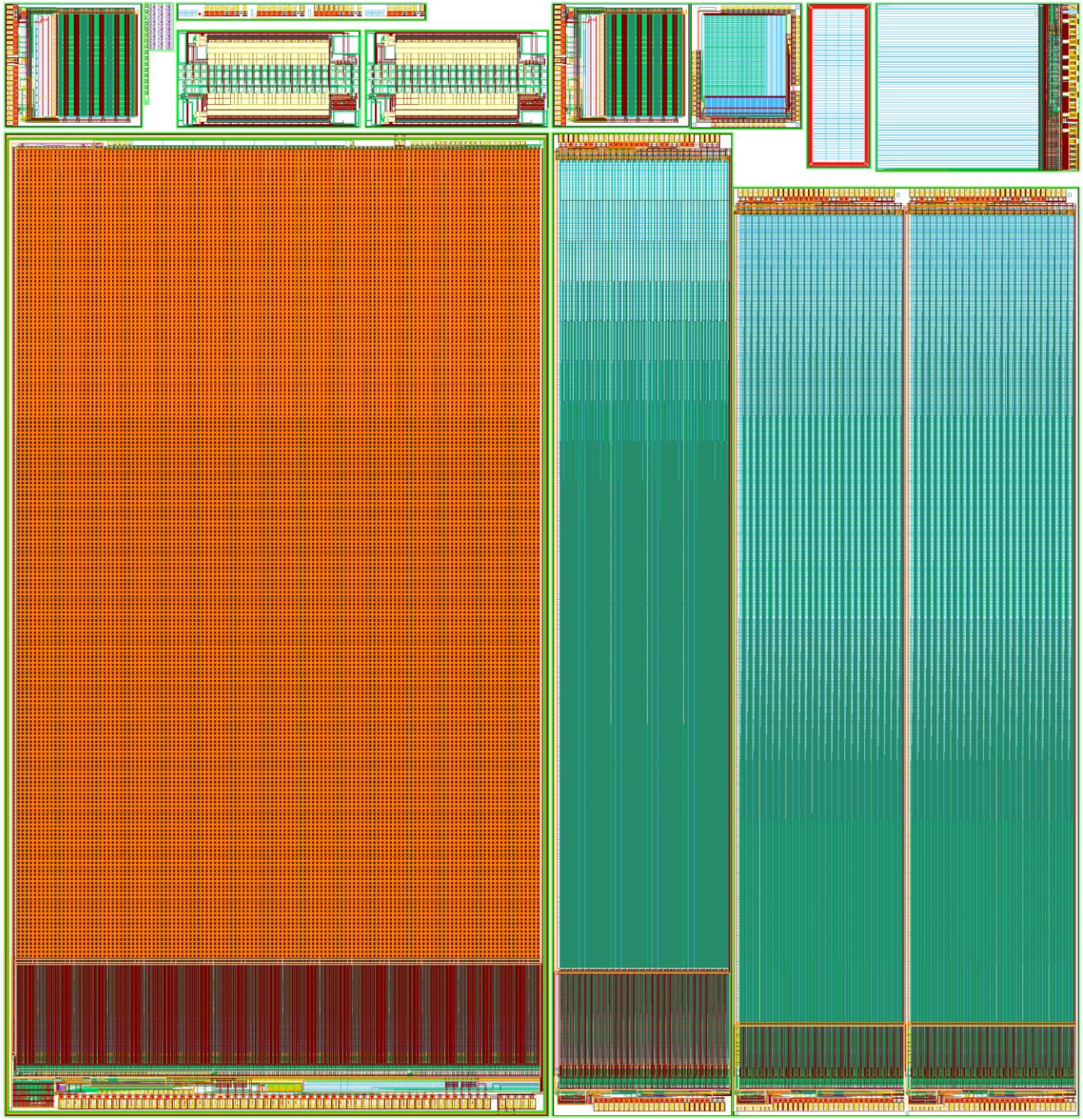


- HVMAPS Matrix
- Untriggered readout, anlog pixels
- Time stamp, threshold, 2 thresholds, amplitude measurement (ramp ADC), time over threshold measurement
- 80um x 80um

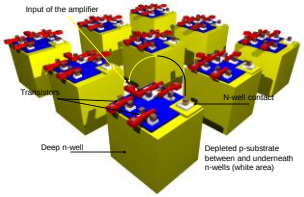


- Simple Matrix
- Untriggered readout, digital pixels
- Time stamp, time over threshold measurement
- 40um x 130um

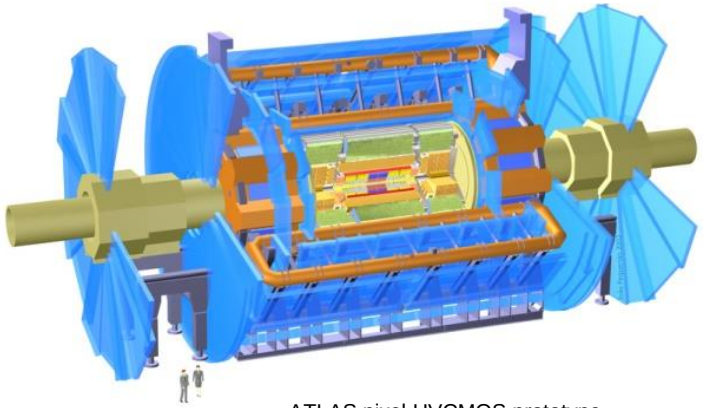




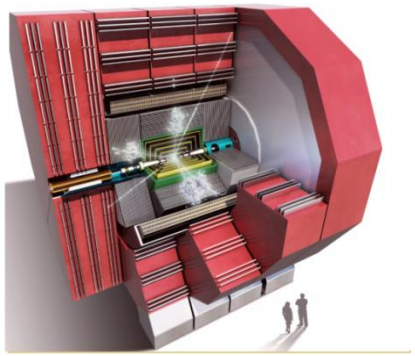
- …



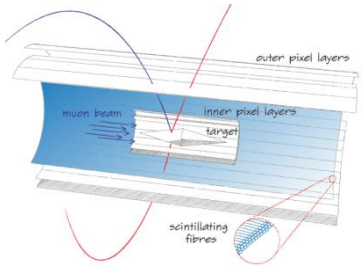
ATLAS detector



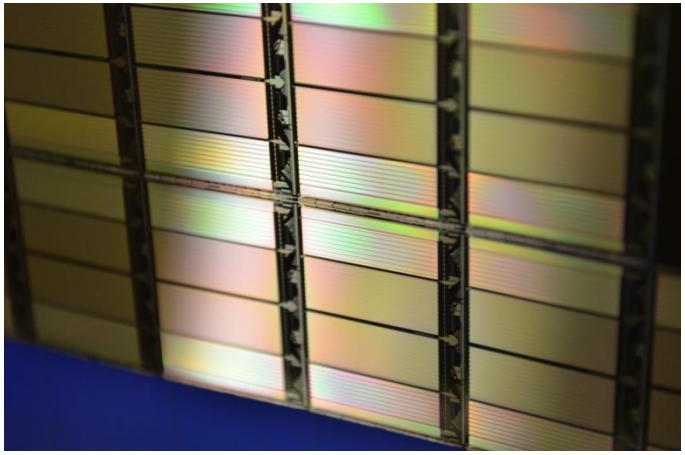
CLIC



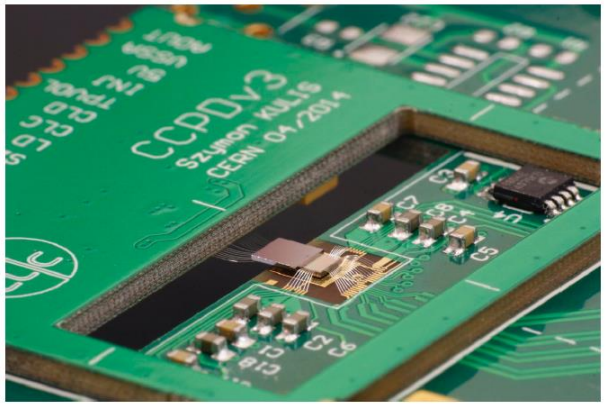
Mu3e detector at PSI



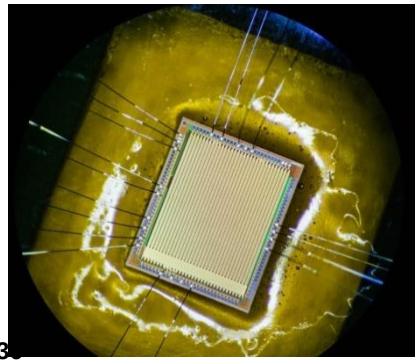
ATLAS pixel HVCMOS prototype

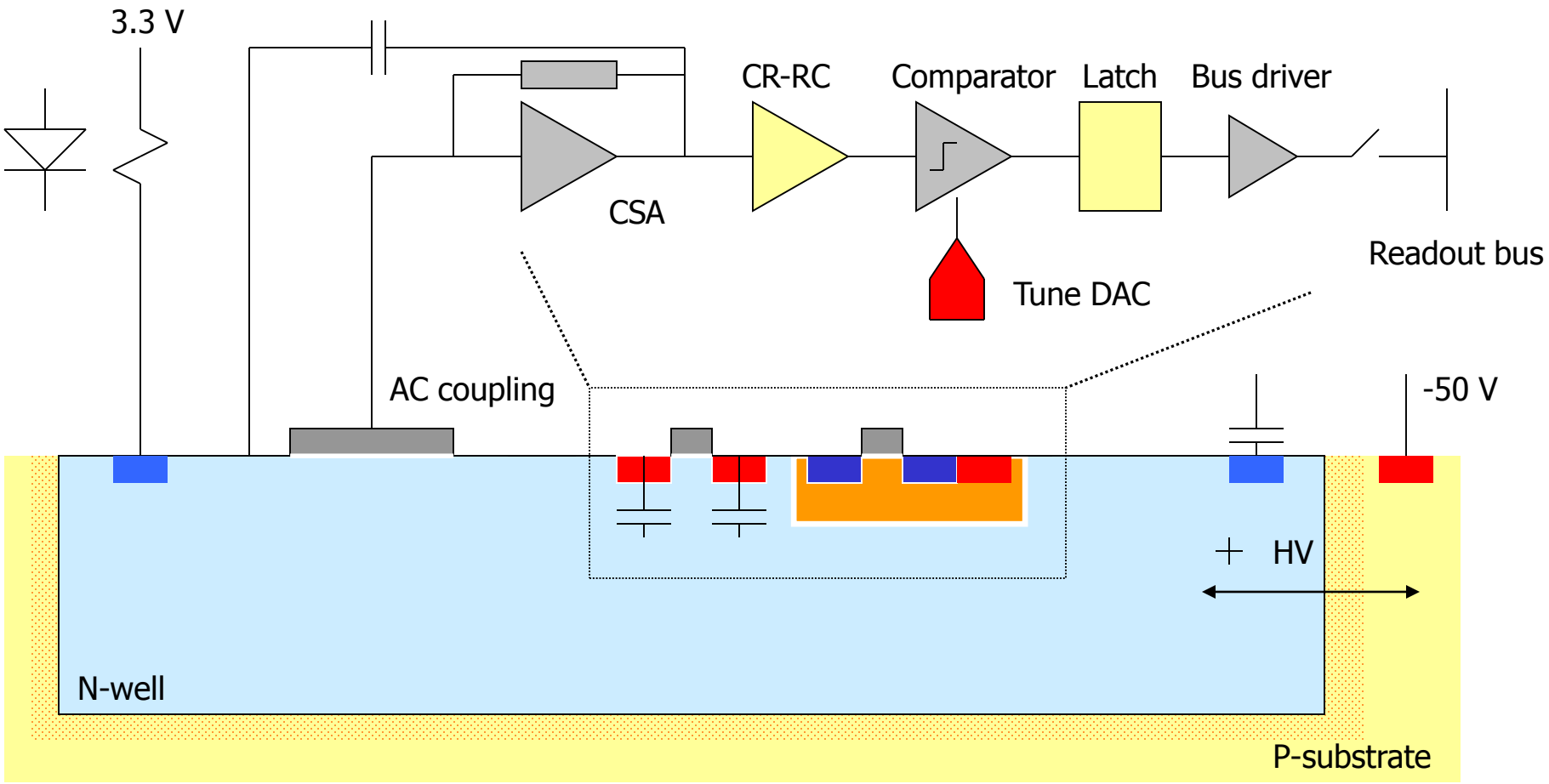


CLICPIX CCPD

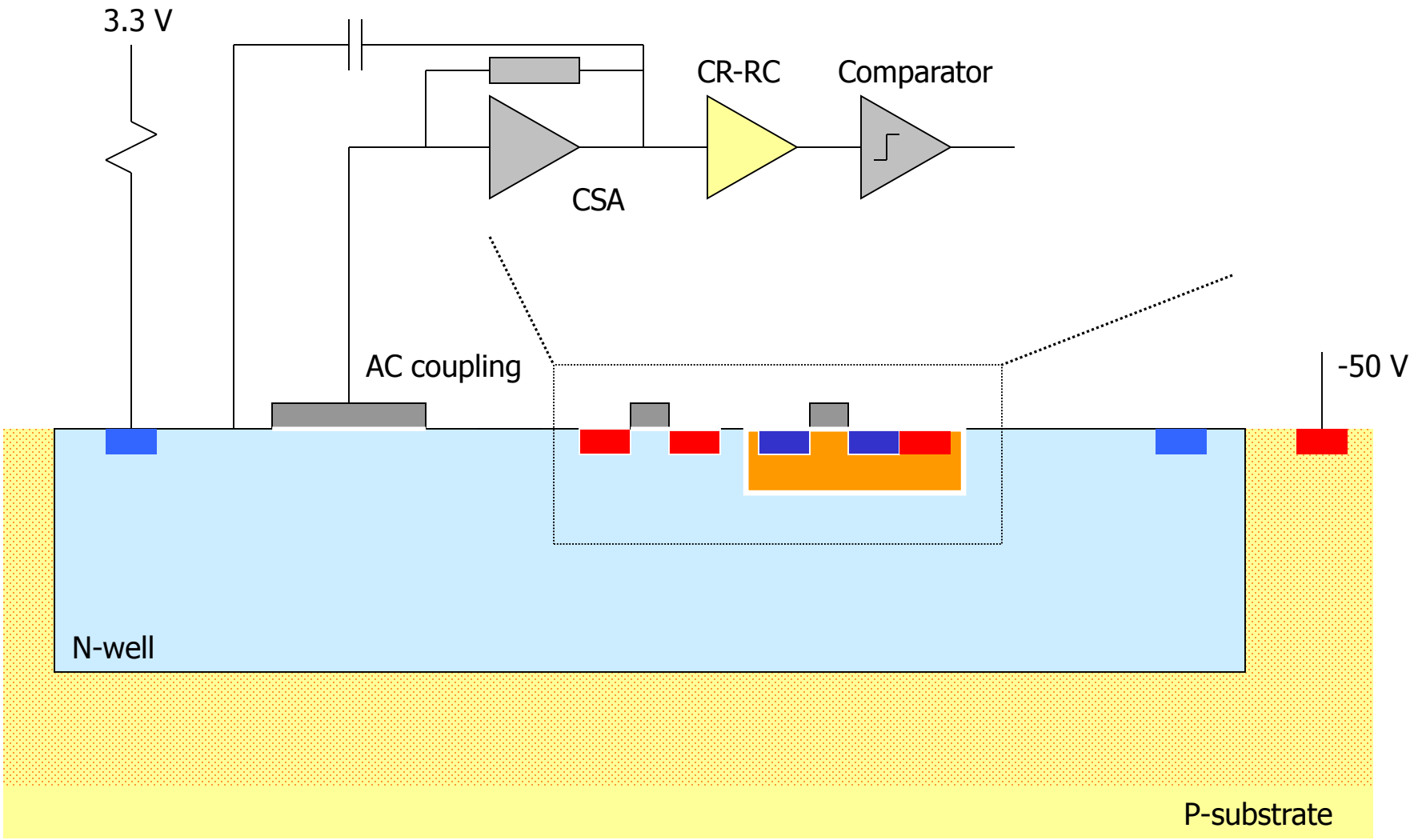


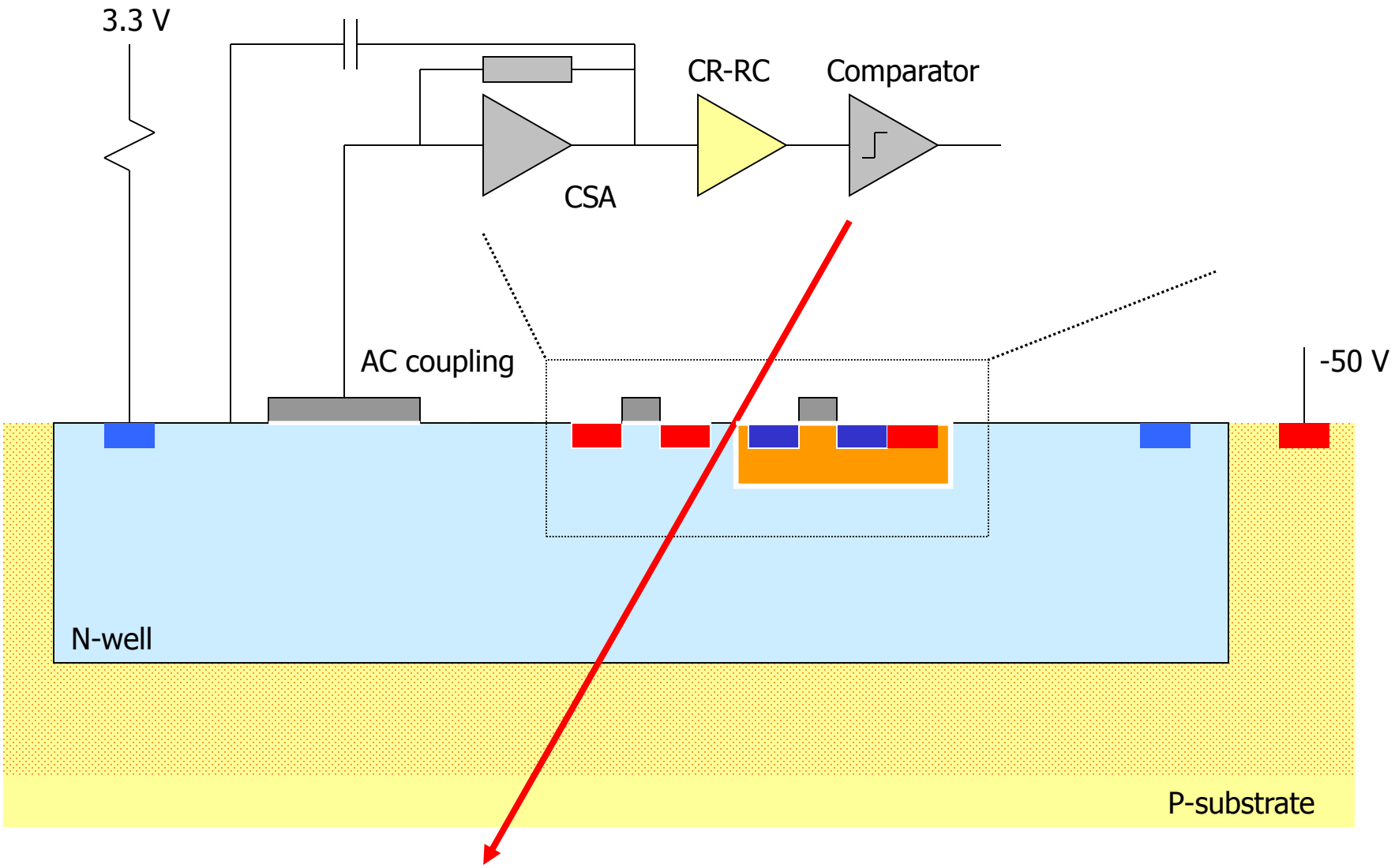
Mu3e-pixel prototype





I. Peric, A Monolithic Pixel Detector
in High-Voltage Technology, Vertex 2006


3.3 V
CR-RC
Comparator
CSA
AC coupling
-50 V
N-well
P-substrate


3.3 V
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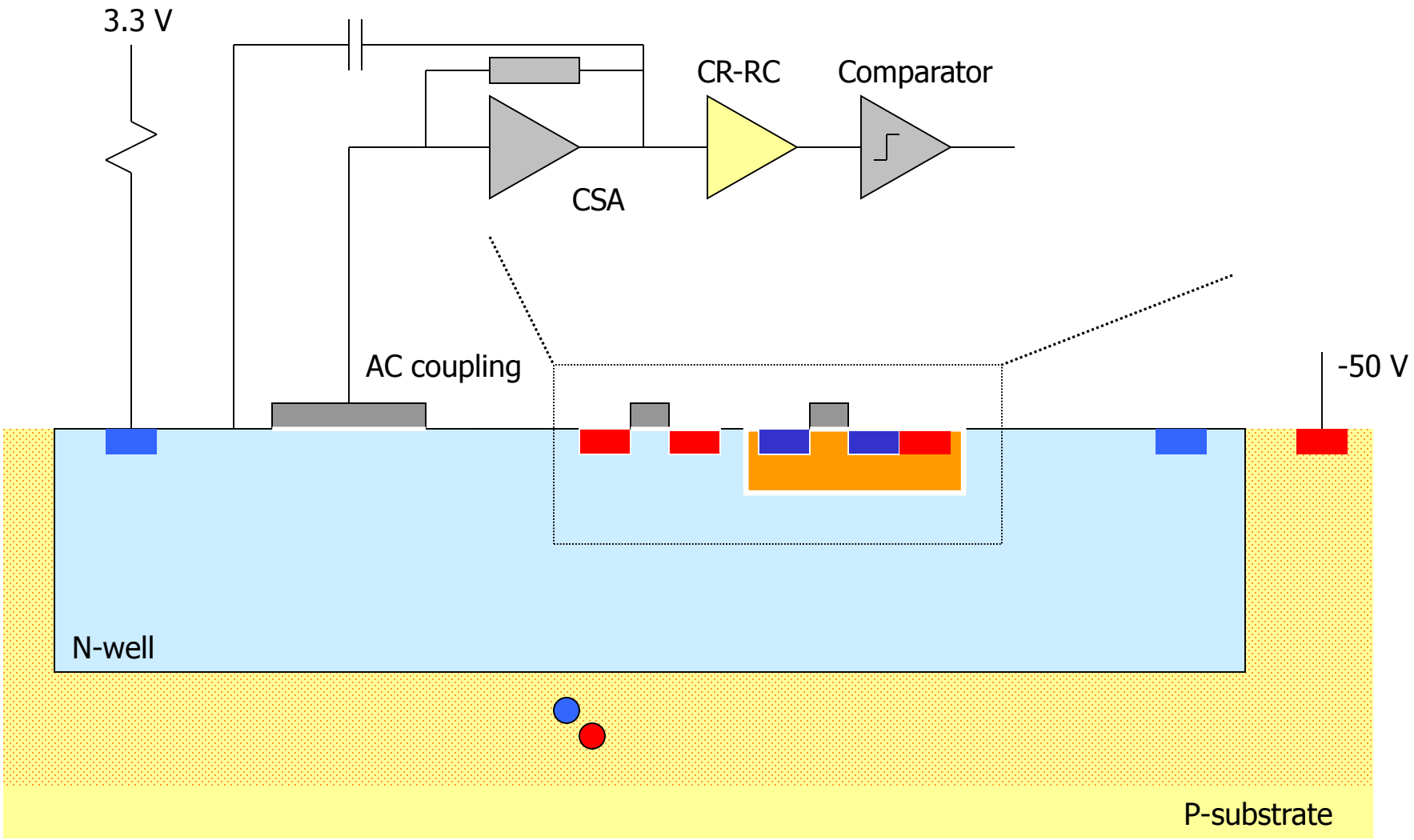
3.3 V
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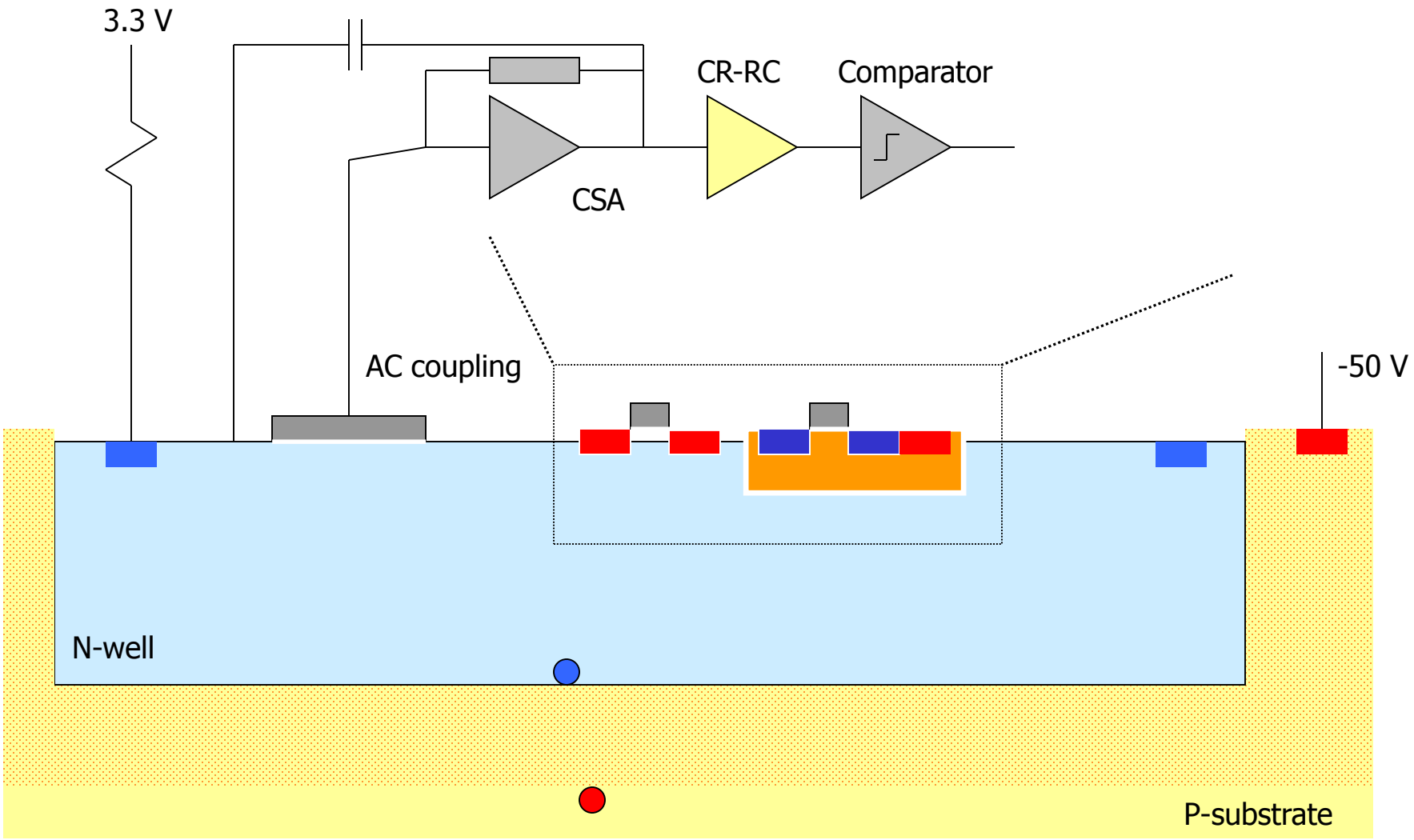
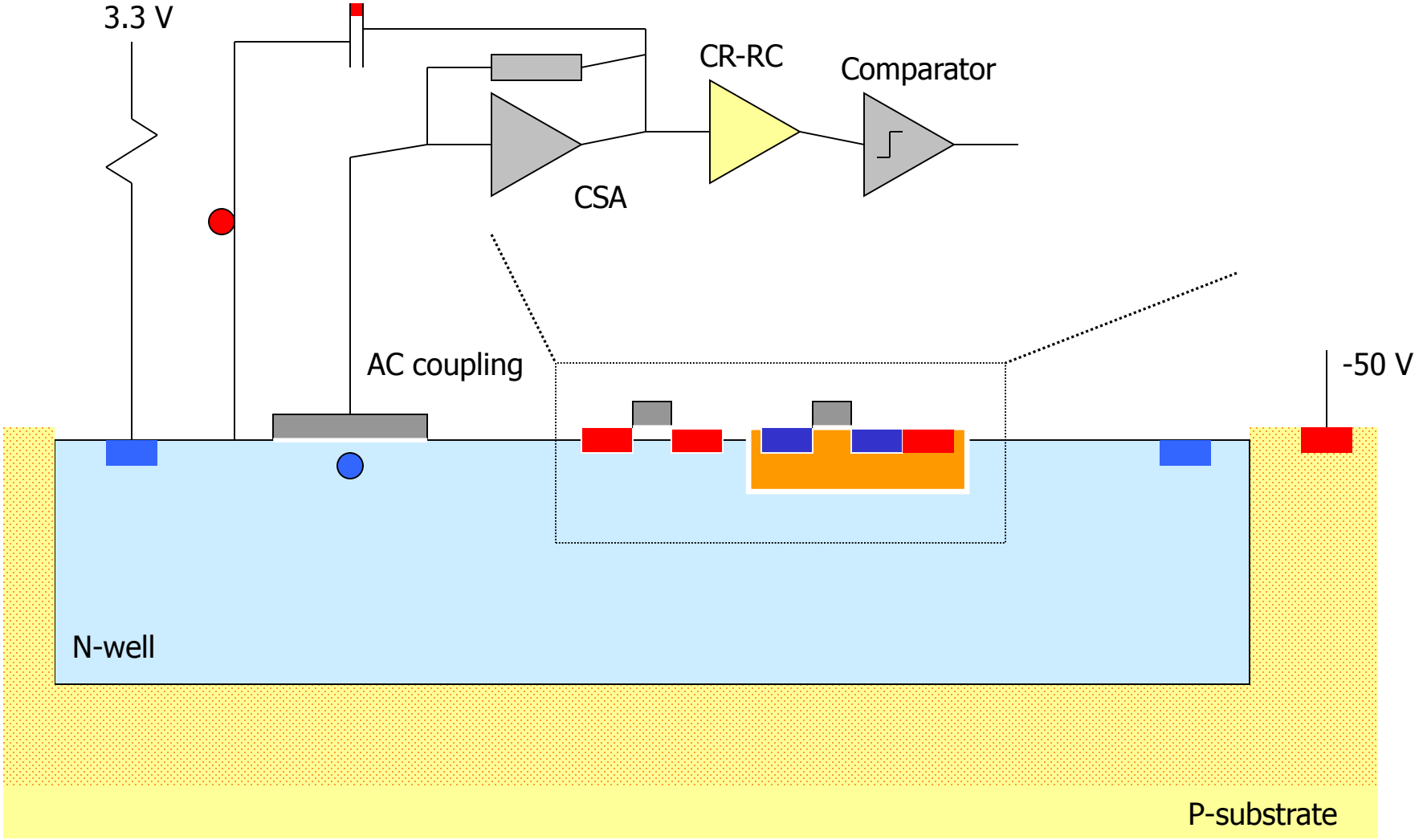

3.3 V
CR-RC
Comparator
CSA
AC coupling
-50 V
N-well
P-substrate


3.3 V
CR-RC
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-50 V
N-well
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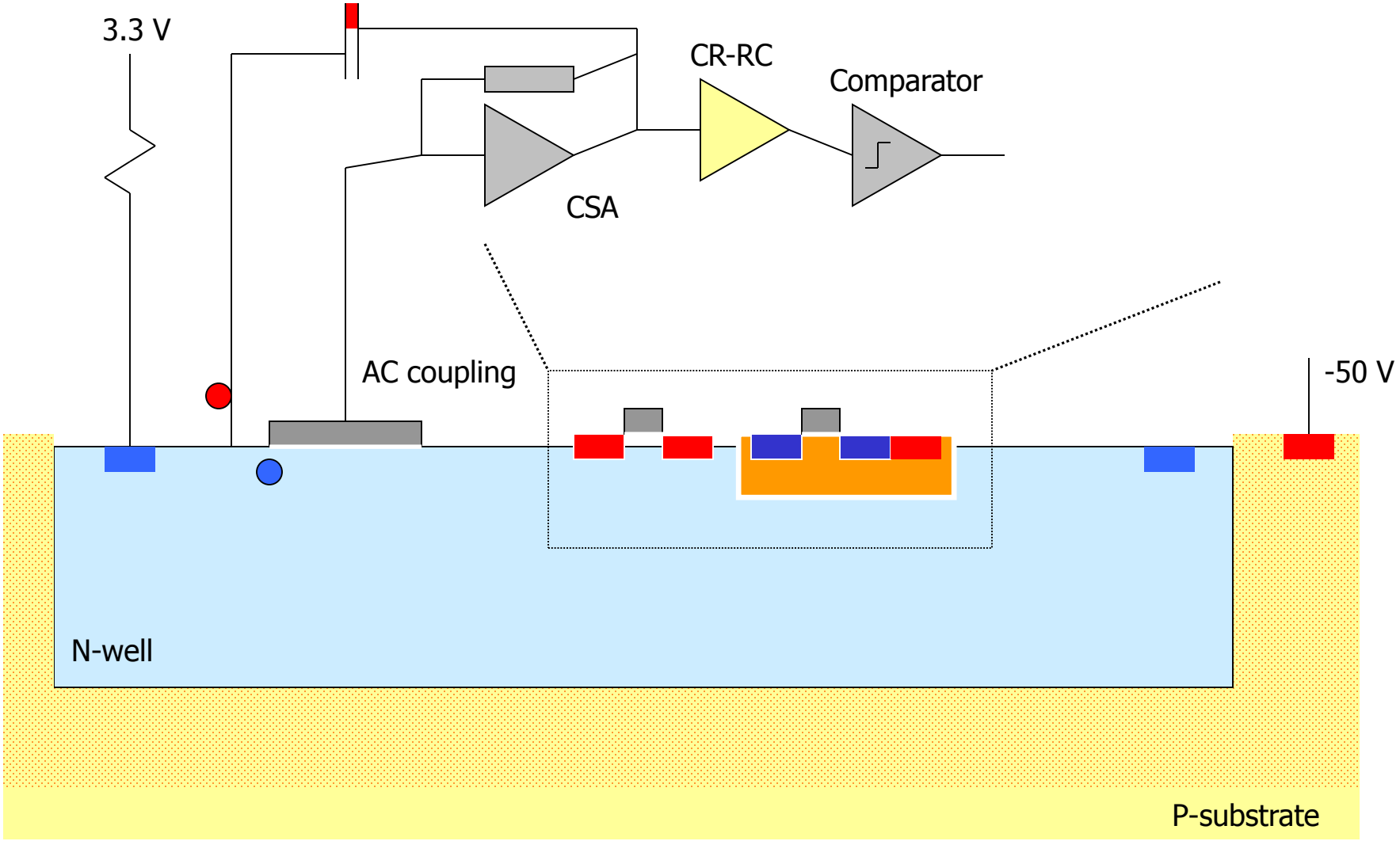
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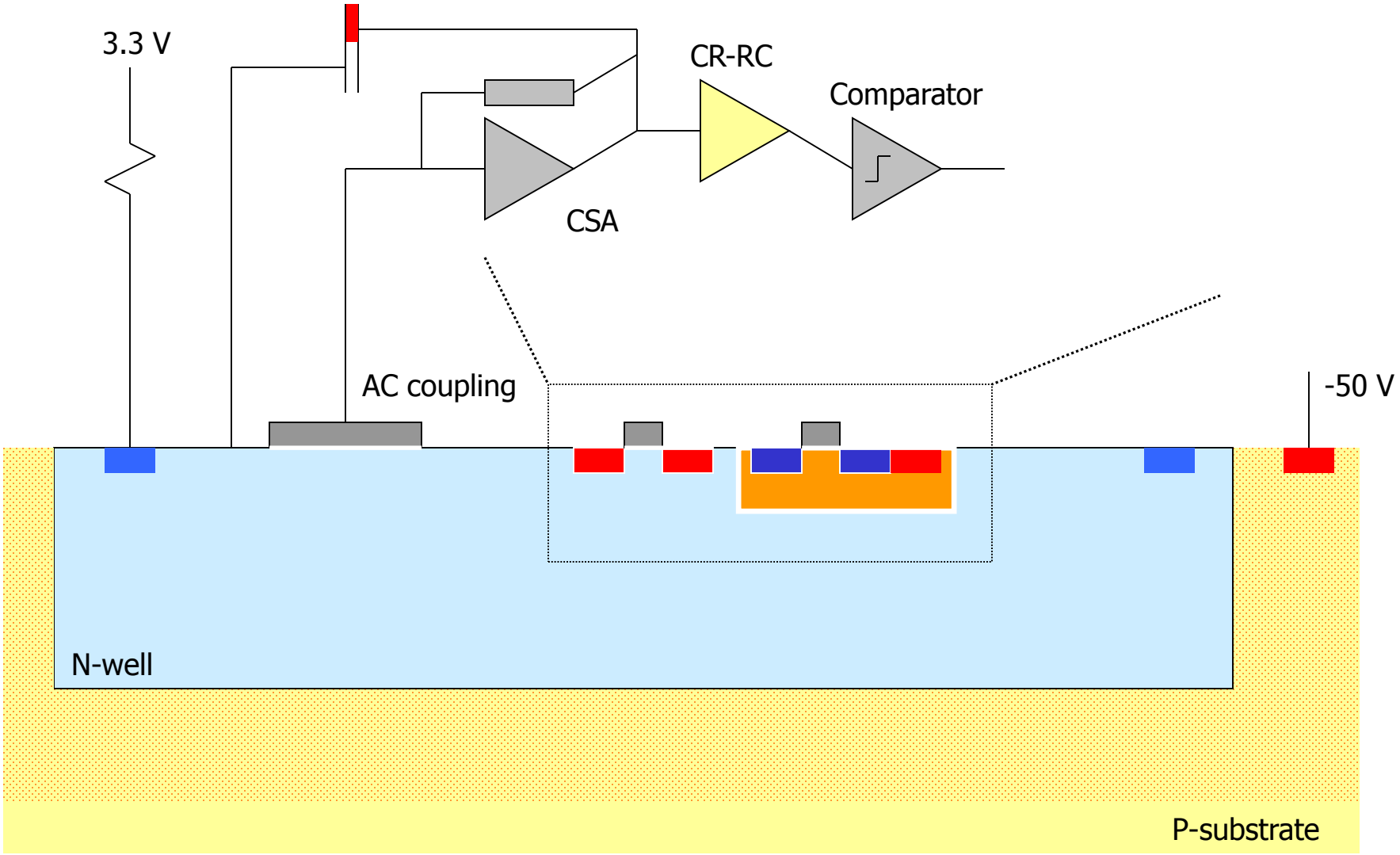
AC coupling
-50 V
N-well
P-substrate


3.3 V
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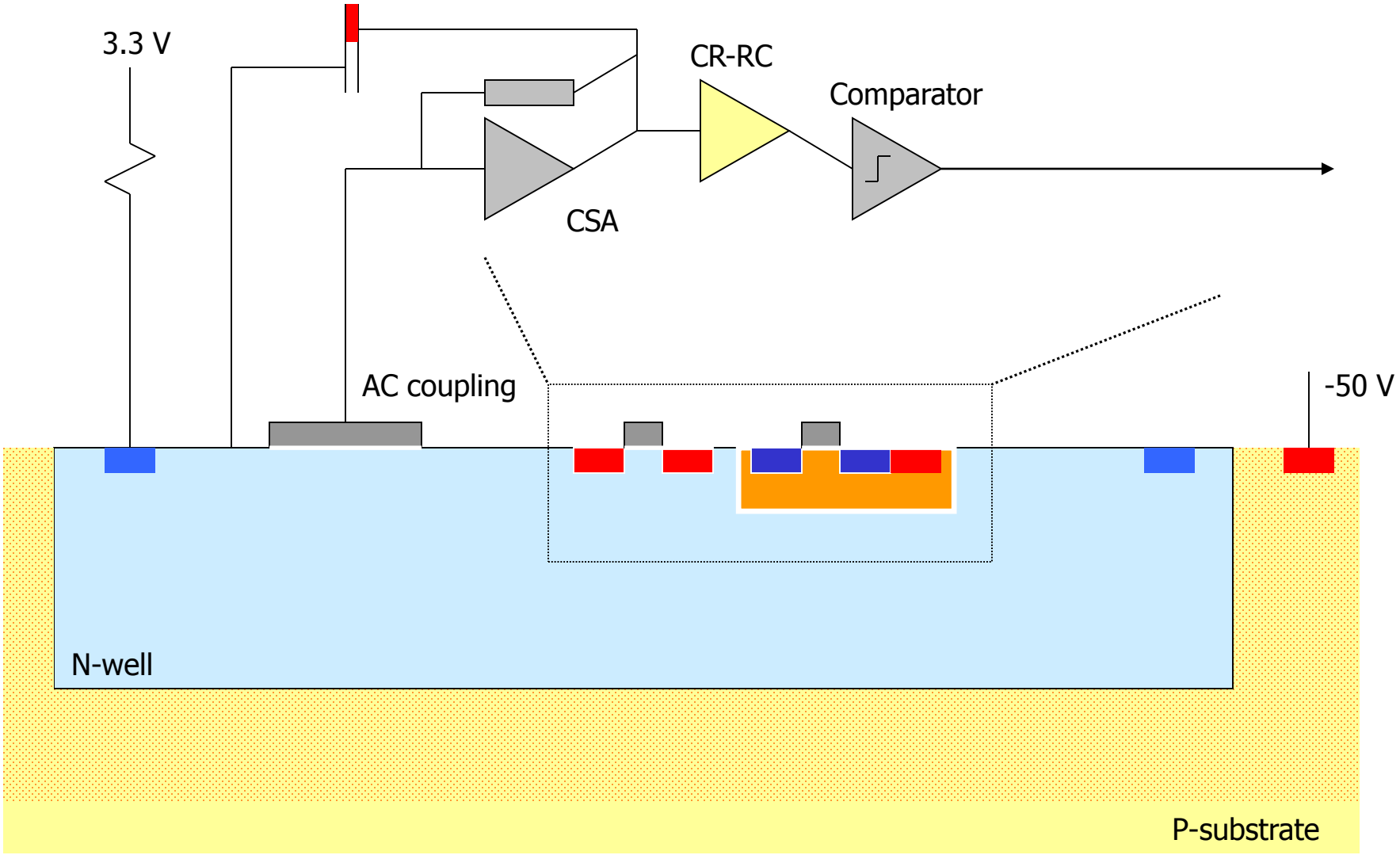
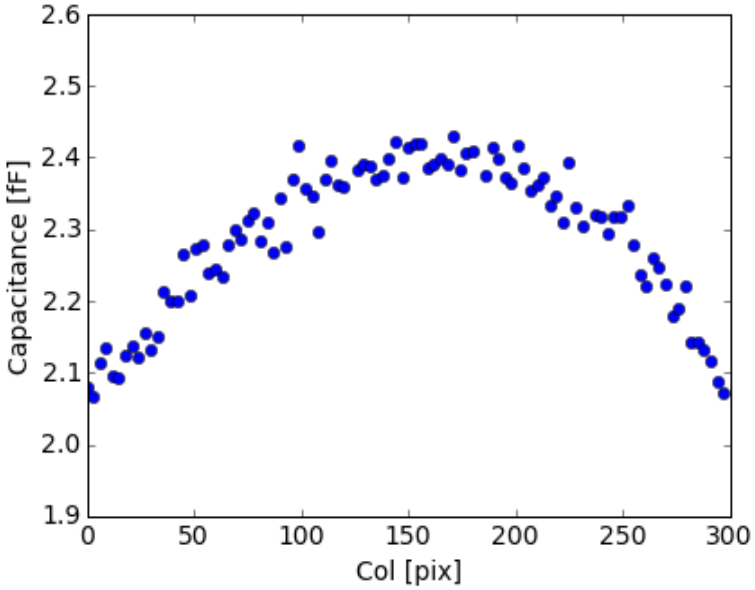

3.3 V
CR-RC
Comparator
CSA
AC coupling
-50 V
N-well
P-substrate

- The H35DEMO has the possibility that external signals are applied to the pixel pads used for the capacitive signal transmission. In this way, the coupling capacitance can be measured for every pixel.
- The coupling capacitive on a large area is quite uniform. The coupling capacitance varies from 2.05fF to 2.4fF, which is a suitable value for signal transmission.

Measurement: Toko Hirono, University of Bonn



Coupling capacitance between HVCMOS pixel pads and FEI4 amplifier pads have been measured (Bonn) along a pixel row of 1.5 cm length.