Design of the **Timepix3**

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8th International Meeting on Front-End Electronics

Outline

- Introduction to Timepix3
- Timepix3 Analog Front-End
- Timepix3 readout architecture
- A new high density and low power digital Library
- Conclusions

2 Collaborations → 21 collaborating institutes

Medipix2

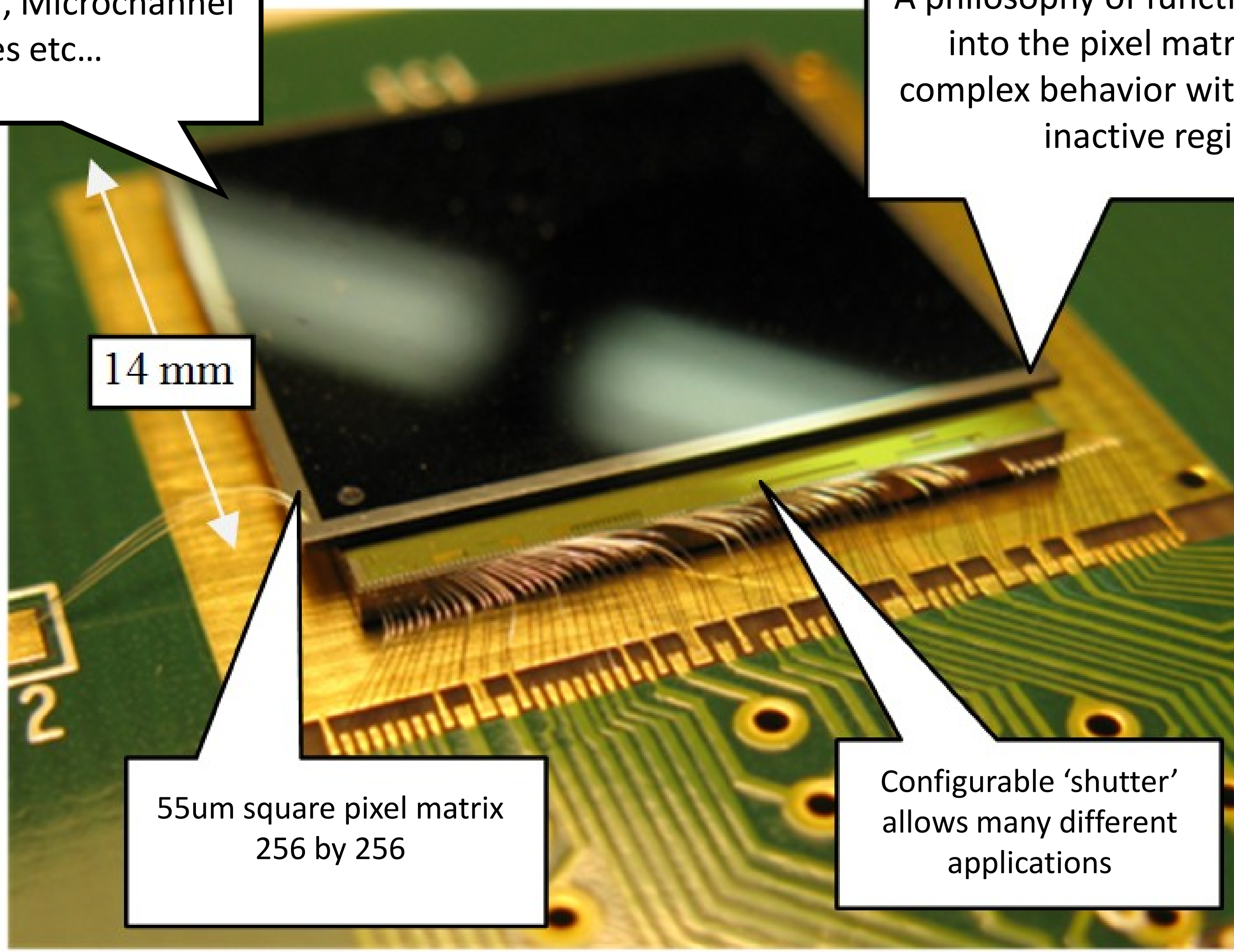
- INFN Cagliari
- CEA-LIST Saclay
- CERN Geneva
- University of Erlangen
- University of Freiburg
- ESRF Grenoble
- University of Glasgow
- University of Houston
- IFAE Barcelona
- Mid Sweden University
- MRC-LMB Cambridge
- INFN Napoli
- NIKHEF Amsterdam
- INFN Pisa
- FZU CAS Prague
- IEAP CTU Prague
- SSL Berkeley

http://www.cern.ch/medipix

Medipix3

- ALMOF Amsterdam
- University of Bogota
- University of Canterbury NZ
- CEA-LIST Saclay
- CERN Geneva
- DESY Hamburg
- Diamond Light Source
- University of Erlangen
- ESRF Grenoble
- University of Freiburg
- University of Glasgow
- ITER
- University of Karlsruhe
- Leiden University
- Mid Sweden University
- NIKHEF Amsterdam
- IEAP CTU Prague
- SSL Berkeley
- VTT Microsystems

The Medipix Chips



Development Path

Medipix1

Medipix2

Timepix

Medipix3

Timepix3

VELOpix

CLICpix

1um SCAMOS 64 by 64 pixels
Photon Counting Demonstrator (1997)

250nm IBM CMOS, 256 by 256 55um pixels
Full photon counting (2002)

Analogue (ToT) and Time Stamping (ToA) (2006)

130nm IBM CMOS, 256 by 256 55um pixels
Photon Counting, Spectroscopic, Charge Summing, Continuous Readout (2009)

Fast front end, Simultaneous ToT and ToA (2012)
<20 Mcounts/cm^2/s

Future LHCb readout – Data driven 40MHz ToT
12Gb/s per chip (2013)
~500 Mcounts/cm^2/s

65nm ? , ~20um pixels
Future Hybrid Pixel Time tagging layer for the LCD project (20??)

Timepix3 Scope

- Several groups in the Medipix3 collaboration have shown interested in a new version of the Timepix (2006) → Timepix3
- Large range of applications (HEP and non-HEP):
  - X-ray radiography, X-ray polarimetry, low energy electron microscopy
  - Radiation and beam monitors, dosimetry
  - 3D gas detectors, neutrons, fission products
  - Gas detector, Compton camera, gamma polarization camera, fast neutron camera, ion/MIP telescope, nuclear fission, astrophysics
  - Imaging in neutron activation analysis, gamma polarization imaging based on Compton effect
  - Neutrino physics
  - Main Linear Collider application: pixelized TPC readout
- Reuse many building blocks from Medipix3 chip (2009)
- Timepix3 is an approved project by the Medipix3 collaboration with an assigned budget (2-engineering runs)
- Design groups: NIKHEF, BONN, CERN

Timepix3 Main Requirements

- Matrix layout: 256x256 pixels (Pixel size 55x55 μm)

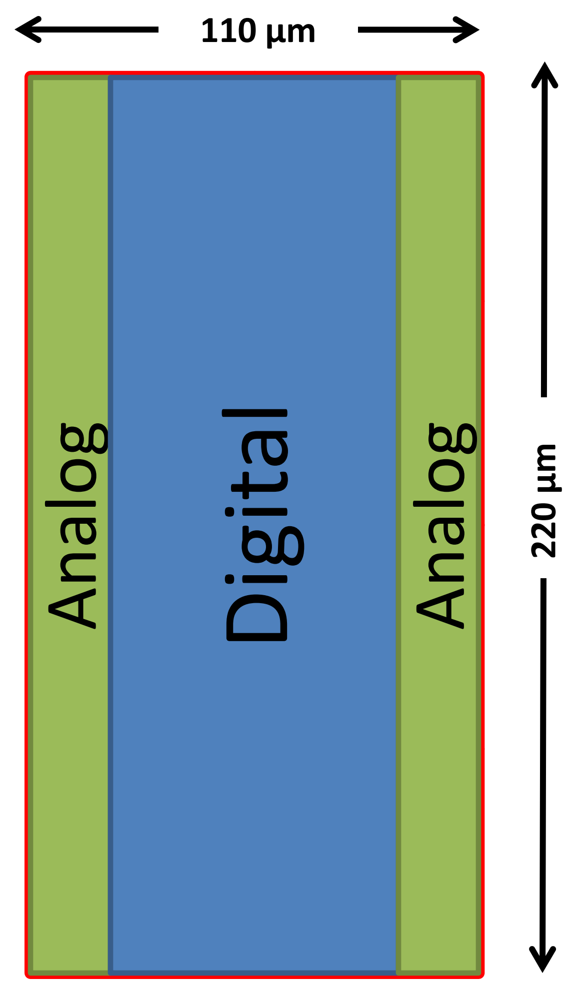
- Time stamp and TOT recorded simultaneously
  - 8-10 bit Energy Measurement (TOT)
    - Standard Resolution 25ns (@40MHz)
    - Energy Dynamic range from 6.4 μs to 25.6 μs (@40MHz)
  - 10-12 bits Slow time-stamp
    - Resolution 25ns (@40MHz)
    - Dynamic range 25.6 μs (10 bit) to 102.4 μs (12 bit)
  - 4 bits Fast time-stamp
    - resolution ~1.5ns (if using on-pixel oscillator running at 640MHz)
    - Dynamic range 25ns

- Sparse Readout

- Technology choice: IBM 130nm DM 3-2-3 or 4-1

The Timepix3 Chip

Readout Chip	TIMEPIX3 (beginning of 2012)
Pixel size	55 x 55 μm^2
Pixel arrangement	256 x 256 (2x4 superpixels)
Sparse readout	YES
PC, TOA or TOT recorded simultaneously	YES (2 at a time) ~40 bit/Hit
Minimum threshold	> 500 e- (1.8 keV)
TOA resolution	> 1.5 ns
Peaking time	< 25 ns
TOT resolution	< 5% channel to channel spread
Technology	IBM 130nm DM 3-2-3 or DM 4-1-3
Power consumption ON	<700 mW (~20 µW/pixel) @1.2 V
Power consumption OFF	<10 mW (Power Pulsing)
Target floorplan	3 sides buttable and minimum periphery
TSVs possibility	YES. Multi-dicing scheme as Medipix3
Count Rate	20x 10^6 x-rays/cm^2/s

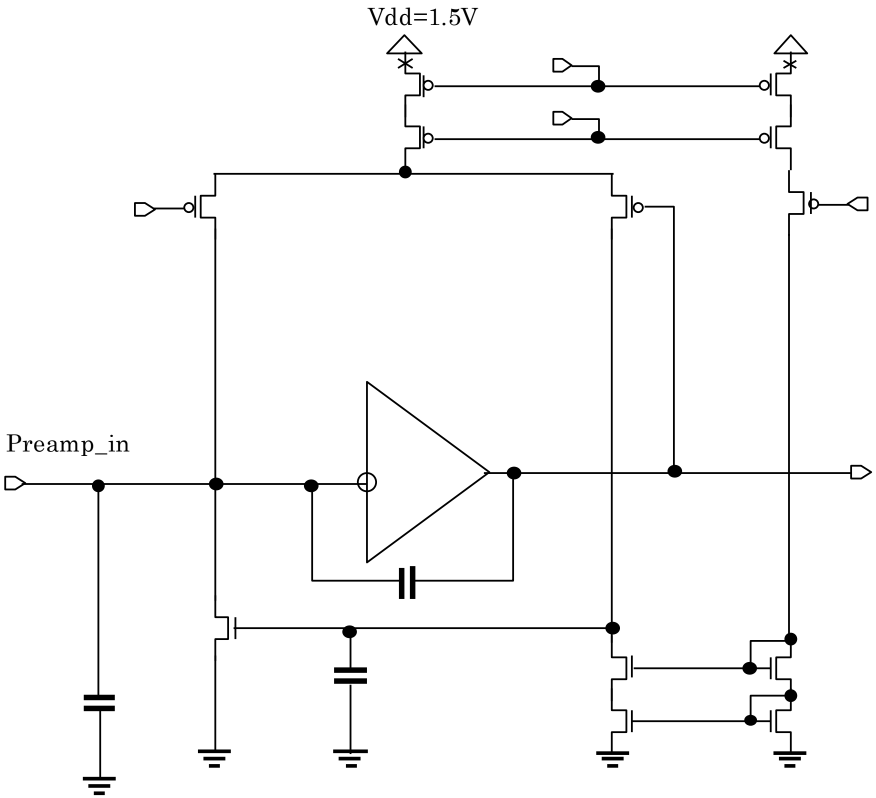


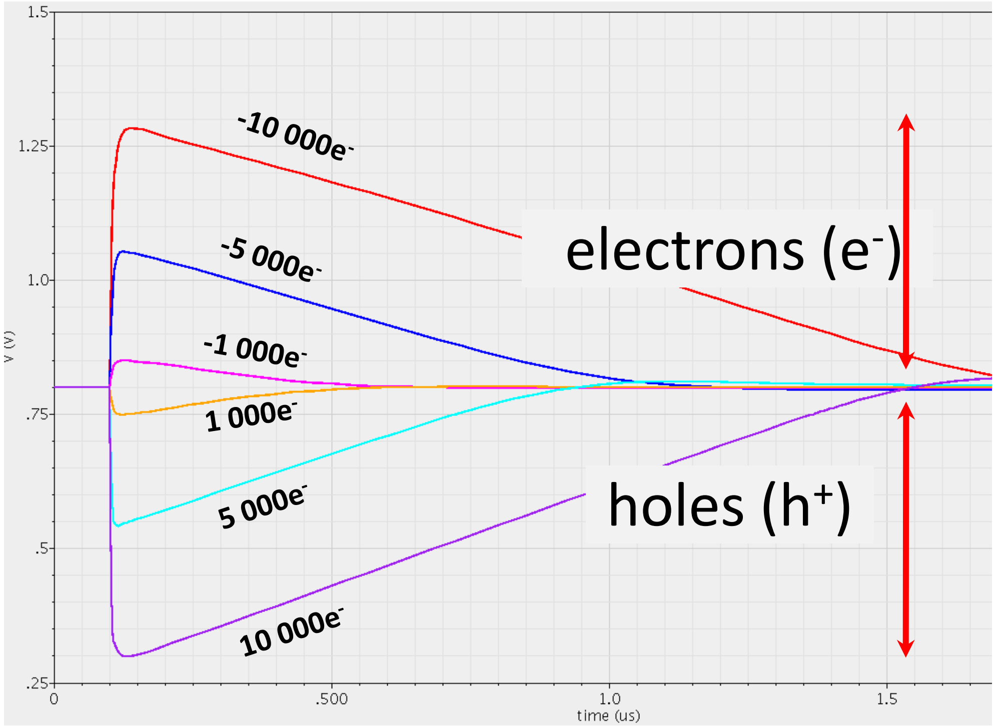
TIMEPIX3 ANALOG FRONT END

Timepix3/VeloPIX pixel FE

- Timepix3 and VeloPix chips can use the same front-end design
- Main requirements:
  - Bipolar input with DC leakage current compensation
  - Small and low power → 55 µm x [10…20] µm and < 10 µW
  - TimeWalk < 25ns → Fast peaking time in Preamp and Fast discriminator (power penalty)
  - Full chip minimum detectable charge as low as possible (< 500e-) → 4 bits threshold tuning and low Preamp Noise (ENC)
  - Precise TOT measurement → Minimize Preamp Noise (ENC)
- An advance version of the schematic has been designed (CERN and NIKHEF)
- Simulation based results are shown in following slides

FE of Timepix3

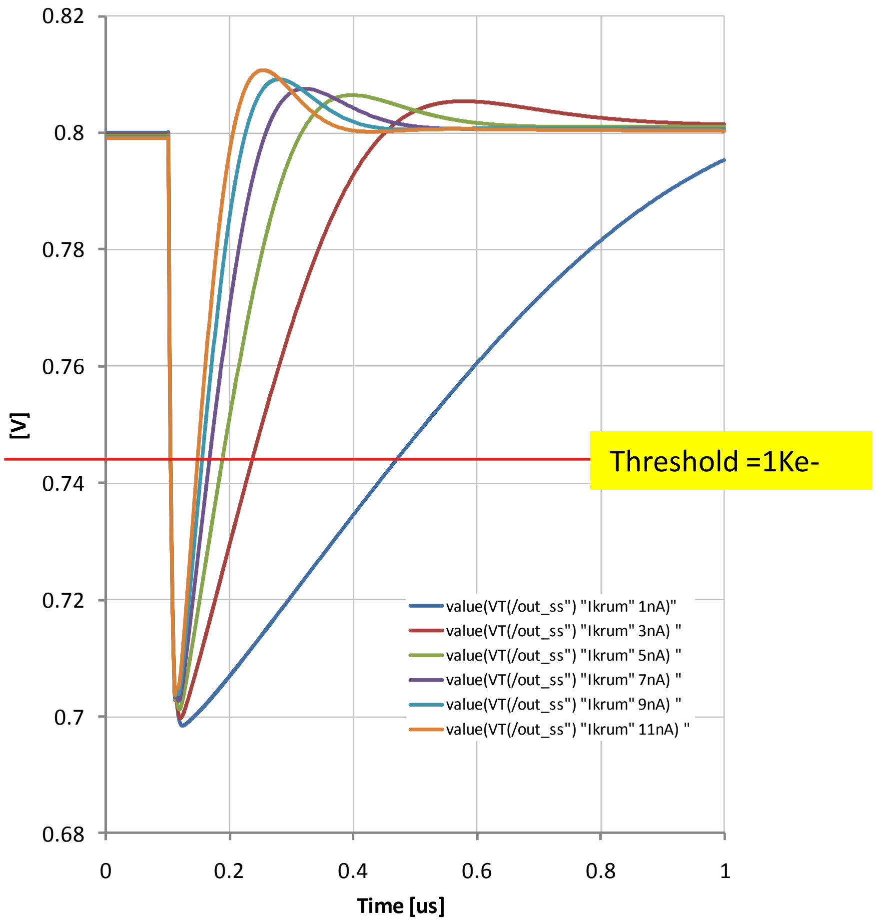


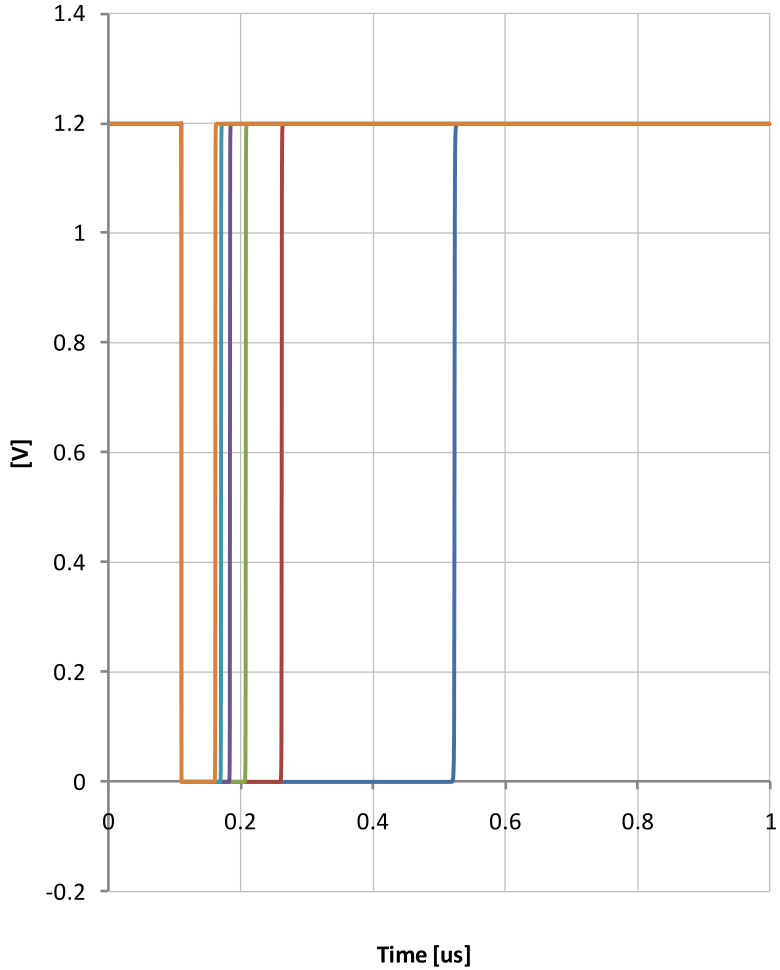


- The design of Timepix3/Velopix FE is based in the Krummenacher FE architecture

Tunable return to zero (Vout vs Ikrum)

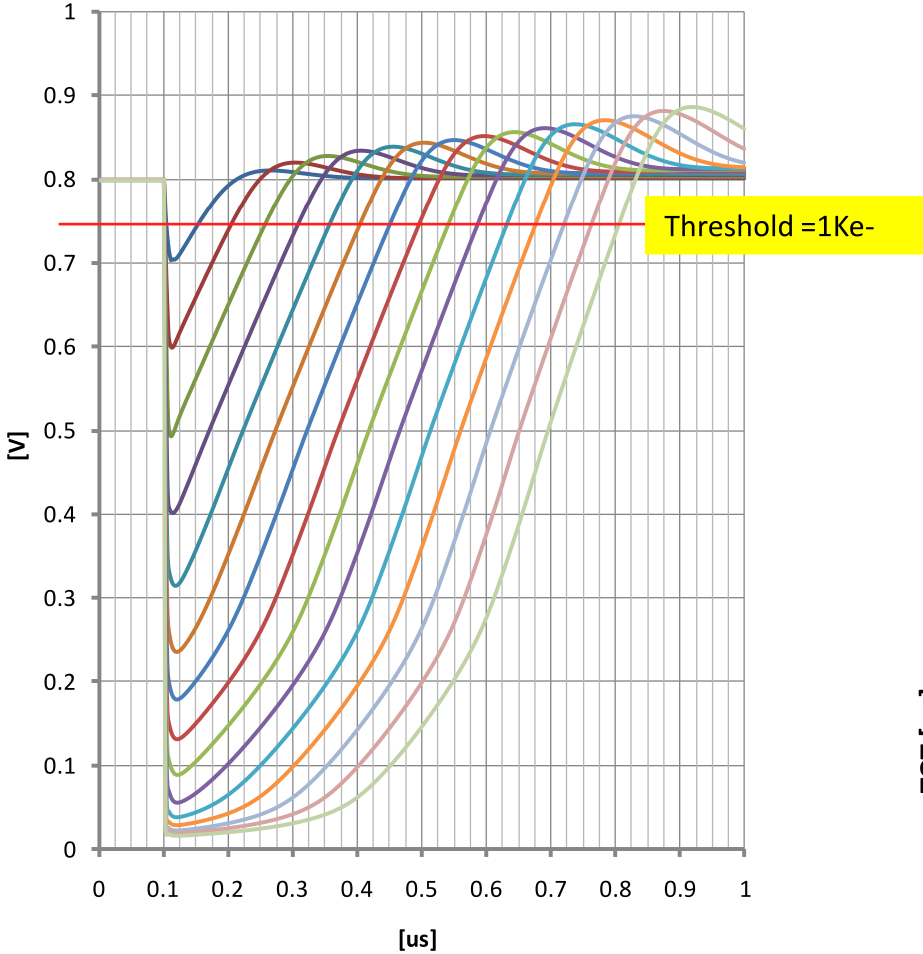
Qin=2ke-



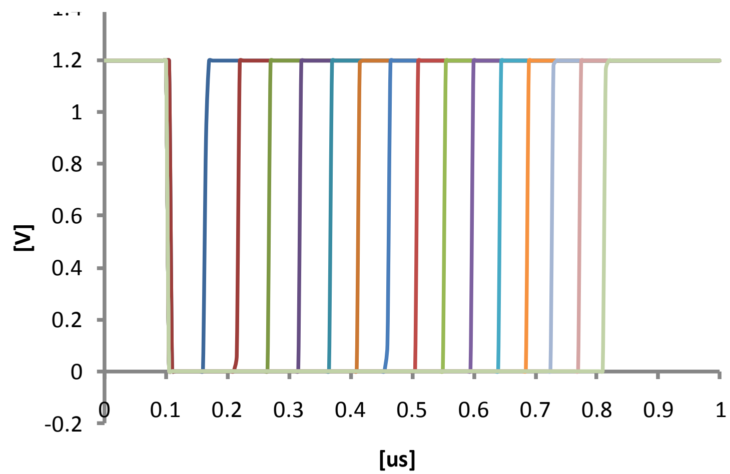


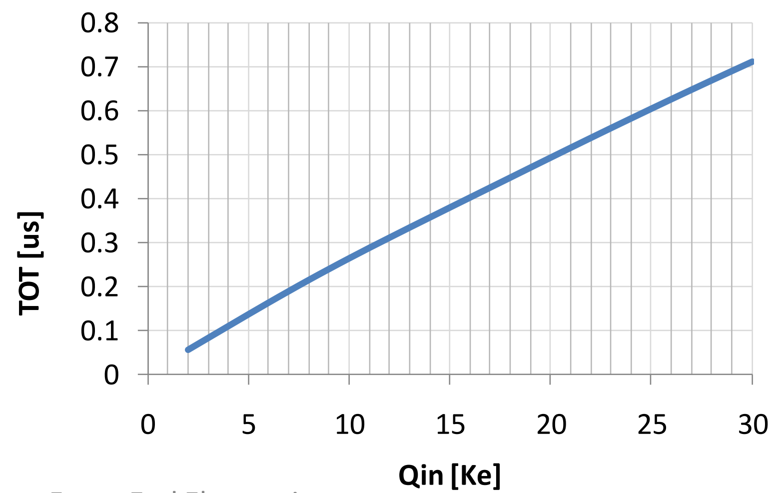
Time-over-threshold response

Preamp Output
Qin=2Ke$^-$ to 30Ke$^-$ @Ikrum=10nA



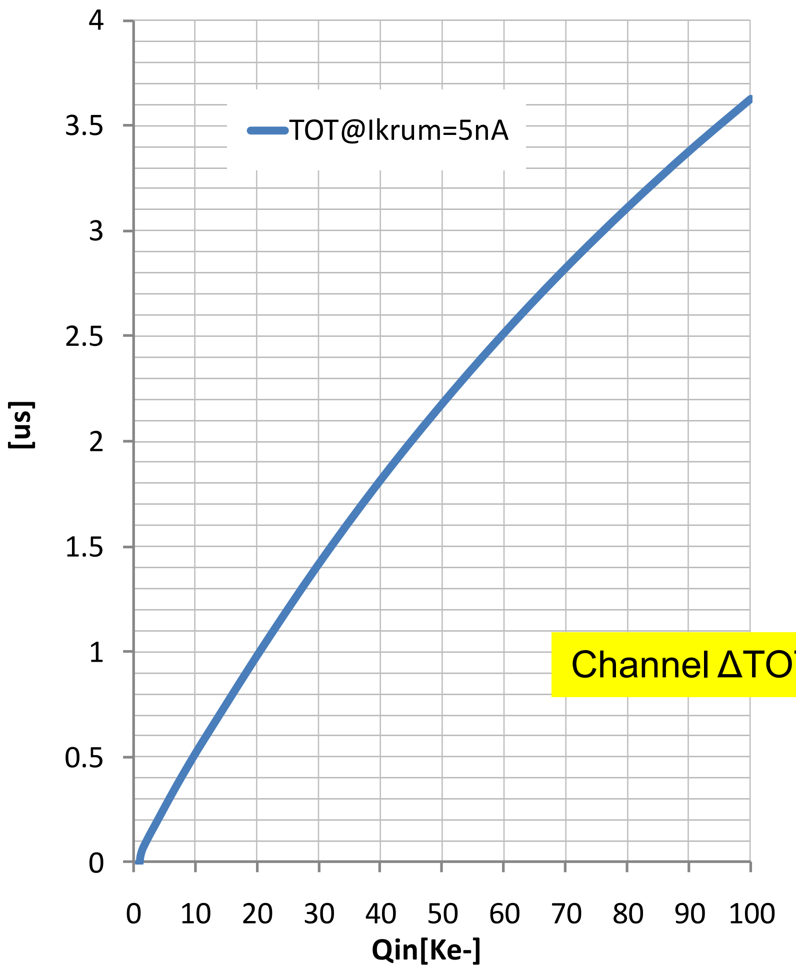
Discriminator Output
Qin=2Ke$^-$ to 30Ke$^-$ @Ikrum=10nA

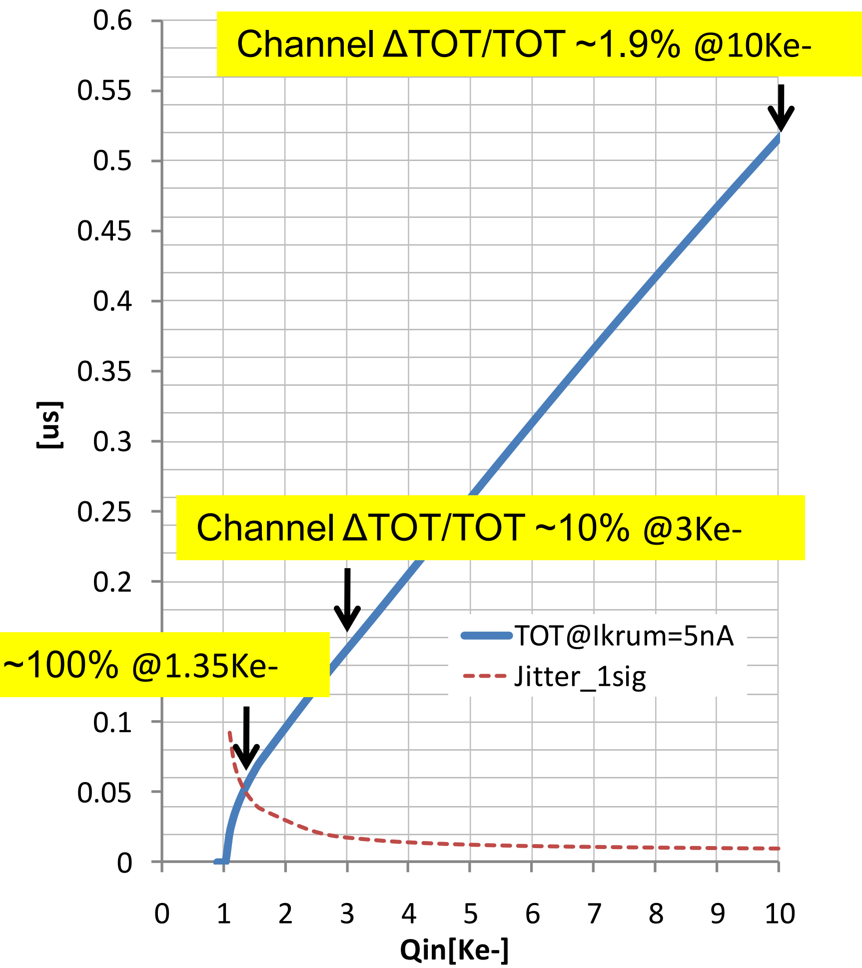




TOT linearity and ΔTOT/TOT

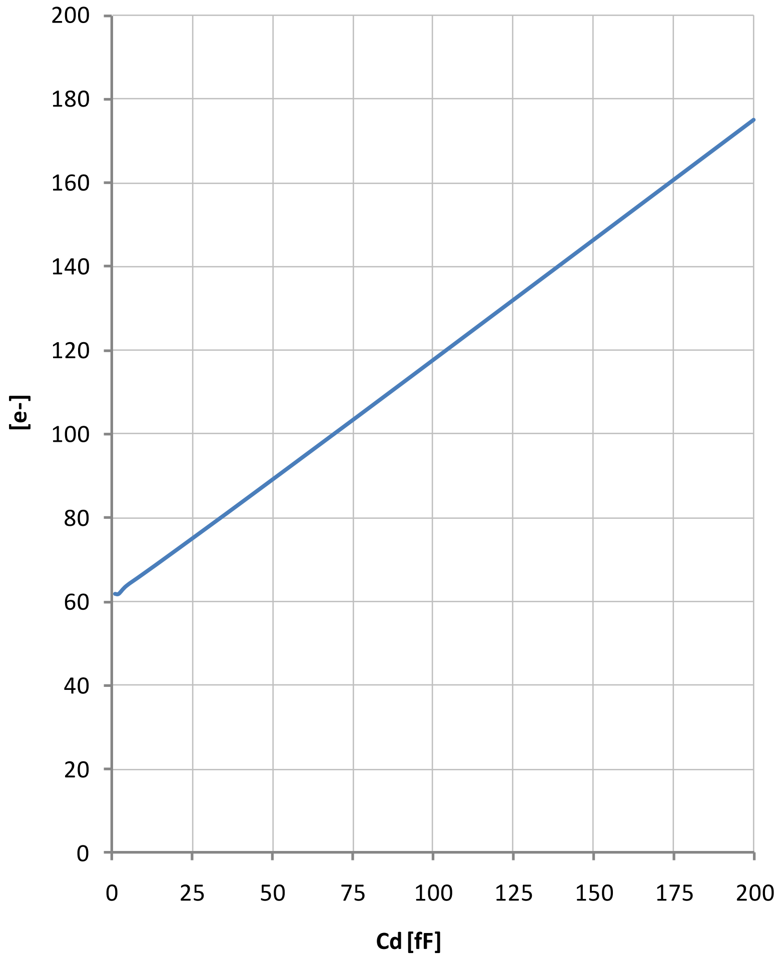
Threshold=1ke$^-$



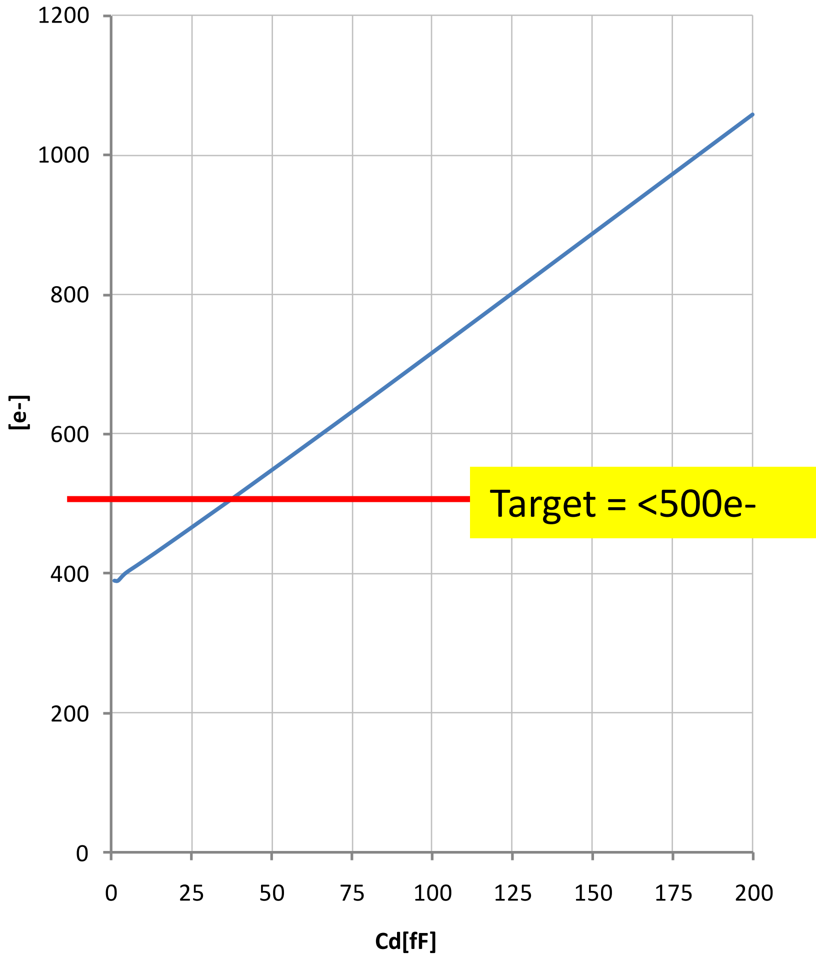


Channel Noise and Minimum detectable Charge

Pixel noise (ENC) vs Cd[fF]

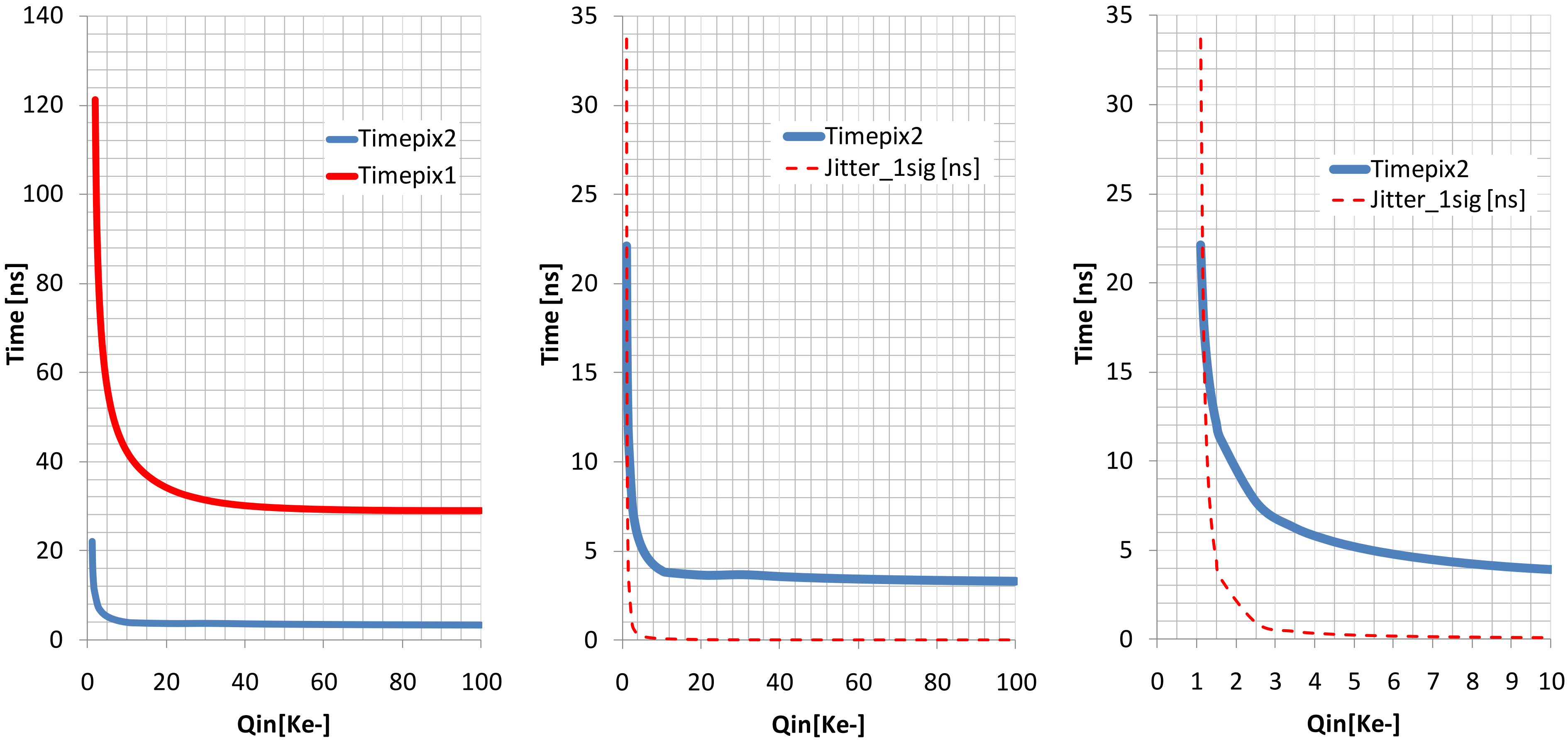


Minimum detectable charge



TimeWalk Simulations

Threshold=1ke^{-}

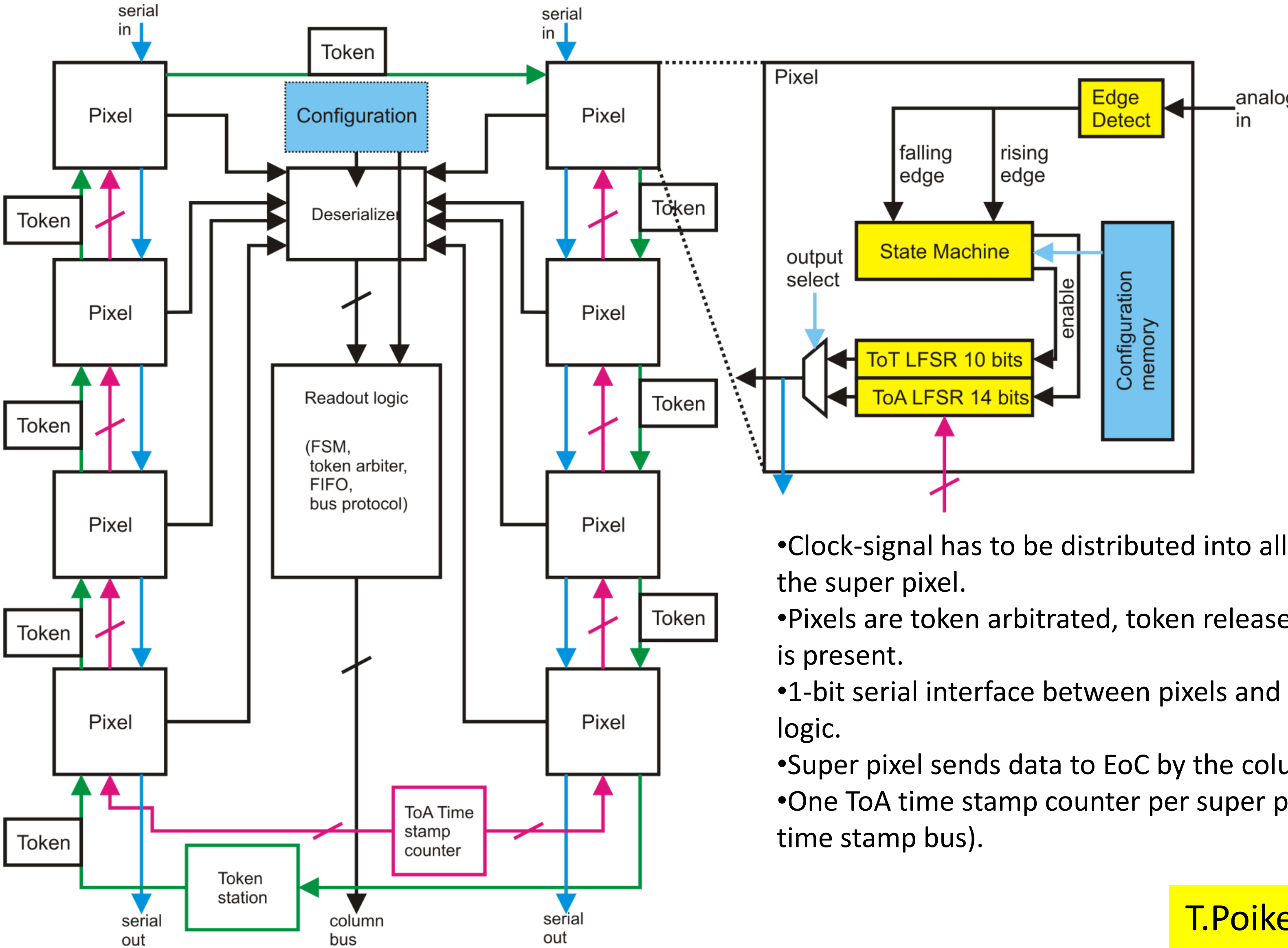


Simulations Summary

	Simulation Results
Pixel size	55 μm x 55 μm
Analog pixel area	55 μm x [10…20] μm
Pixel matrix	256 x 256
Input charge	Bipolar (h^+ and e^-)
Leakage current compensation	YES
Detector capacitance (Planar detector)	< 50 fF
Peaking time	<25ns if Cd<70fF
Preamp output linear dynamic range	< 15 Ke^-
Timewalk	<25ns [@ Qin>Threshold]
Return to zero (Tunable)	YES (ΔIkrum)
TOT linearity and range	Monotonic up to ~150 Ke^- @Ikrum 10nA
Return to zero full chip spread (TOT spread)	< 5%
ENC (σ_{ENC})	0.57*Cd[fF]+61 [e-] → ~75 e^- @ Cd=25fF
# Thresholds	1
Discriminator response time	<5ns [if Qin>Threshold + 5 Ke^-]
MC simulated Threshold spread	~200 e^-
Threshold spread after tuning (4 bits)	~20 e^-
Full chip minimum detectable charge	6*sqrt(ENC^2+Threshold_mismatch^2) → ~475 e^- @ Cd=25fF
Pixel analog power consumption	8.4 μW static (Preamp 3.6 μW and 4.8 μW Discriminator) 2.4 μW dynamic (only @ HIT)

TIMEPIX3 READOUT ARCHITECTURE

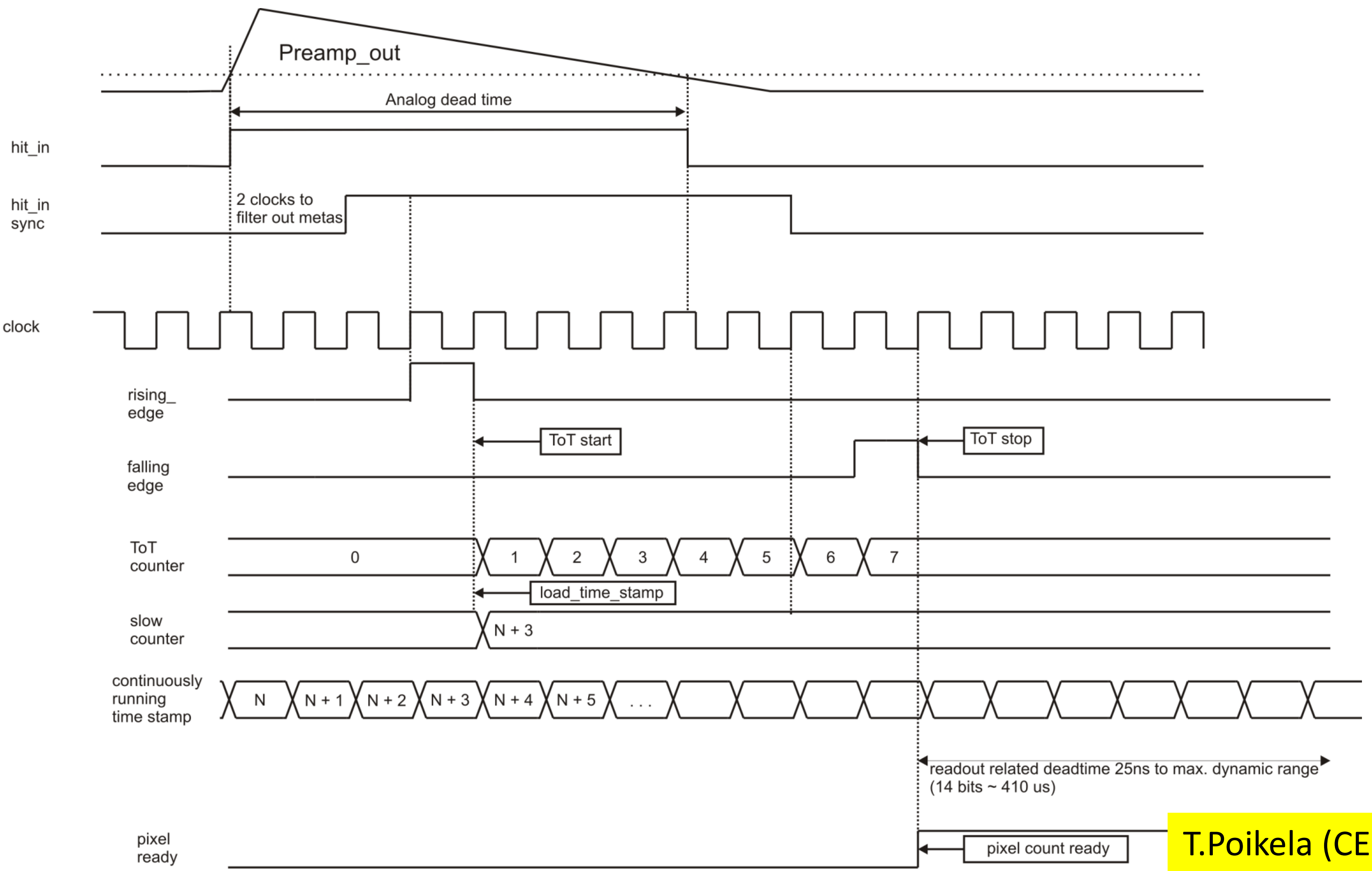
Super Pixel and Pixel



- Clock-signal has to be distributed into all modules in the super pixel.
- Pixels are token arbitrated, token released when a hit is present.
- 1-bit serial interface between pixels and the readout logic.
- Super pixel sends data to EoC by the column bus.
- One ToA time stamp counter per super pixel (or global time stamp bus).

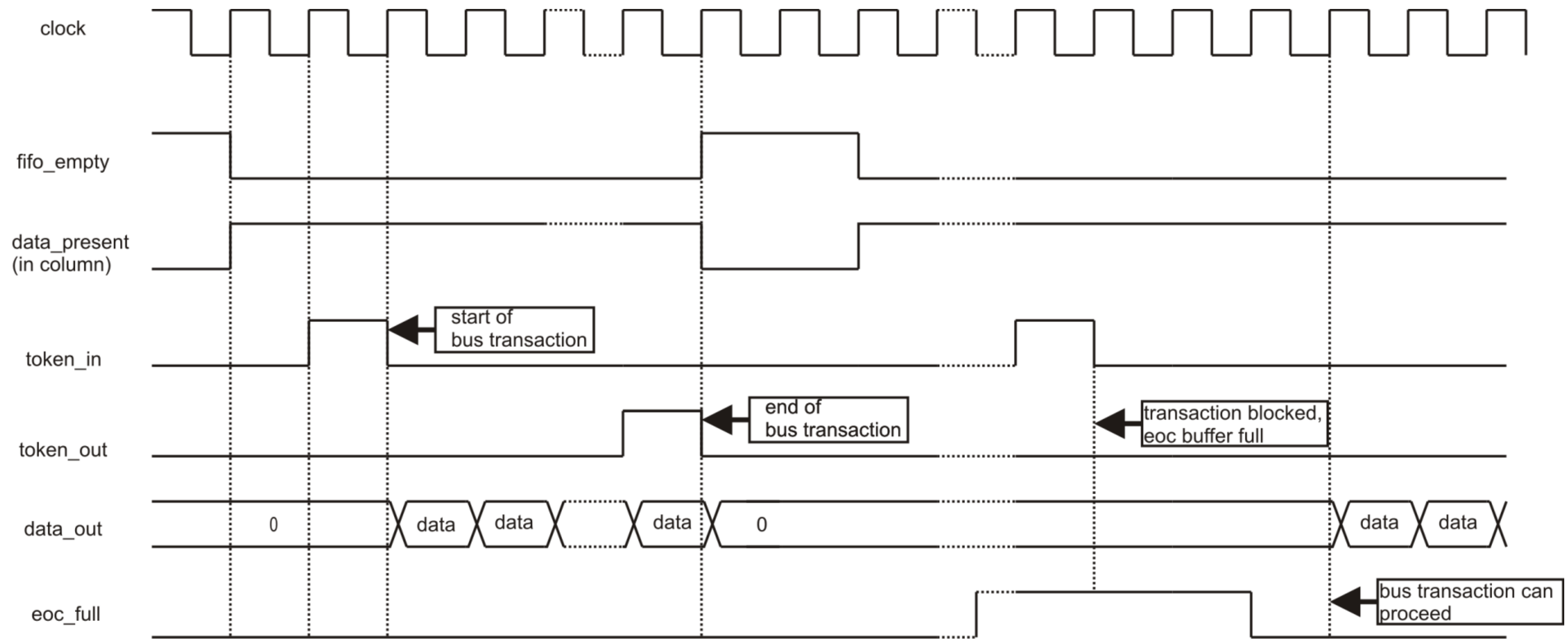
T.Poikela (CERN)

Timing Diagram of Digital Pixel



T.Poikela (CERN)

Super Pixel-to-EoC data transport



- Bus protocol does not allow any data overflows in the periphery. If EoC is full, no data is transmitted.
- Protocol requires a counter in the super pixel to count the number of words per bus transaction (max 3-bit counter)
- Global signals in Double Column:

Data bus	5b/9b (not fixed yet)
EoC Full	1b
DataPresent	1b
RefClk	1b
Reset	1b
Shutter	1b
Time stamp	14b (or implemented with local counter)
Total	10b – 28b

T.Poikela (CERN)

To sum it up: Pixel/ Super Pixel Features

Feature	Description
ToT Counter 10 bits (Pixel)	Resettable LFSR for ToT/ event count.
ToA Counter 14 bits (Pixel)	Resettable LFSR / parallel load register (40MHz)
Fast ToA Counter 4 bits (Pixel)	Binary Counter (640MHz)
Event count/Integral ToT mode	Event count 10 bits, ToT 14 bits in this mode.
Configuration Register (~10 bits) (Pixel)	Size depends on the features in a pixel.
Fast counter reset (Pixel)	Reset in 24 clock cycles (600 ns).
Shutter-signal (Pixel)	Controls data taking. (See Timepix1)
Adjustable ToT/ToA clock. (Pixel?/Super Pixel?/EoC?)	Make ToA/ToT independent of each other.
Output select (either from 10b/14b/both counters)	Makes it possible to read out only ToA or ToT information if required.
Configurable pixel-to-super pixel FIFO dead time.	Done by adjusting the shift counter of deserializer in the super pixel.
User-enabled readout mode (Super pixel)	Closing the shutter starts the readout in user-enabled mode (Event count mode).
Continuous readout mode (Super pixel)	Readout operates independently of shutter-signal.

A HIGH DENSITY AND LOW POWER STANDARD CELL LIBRARY

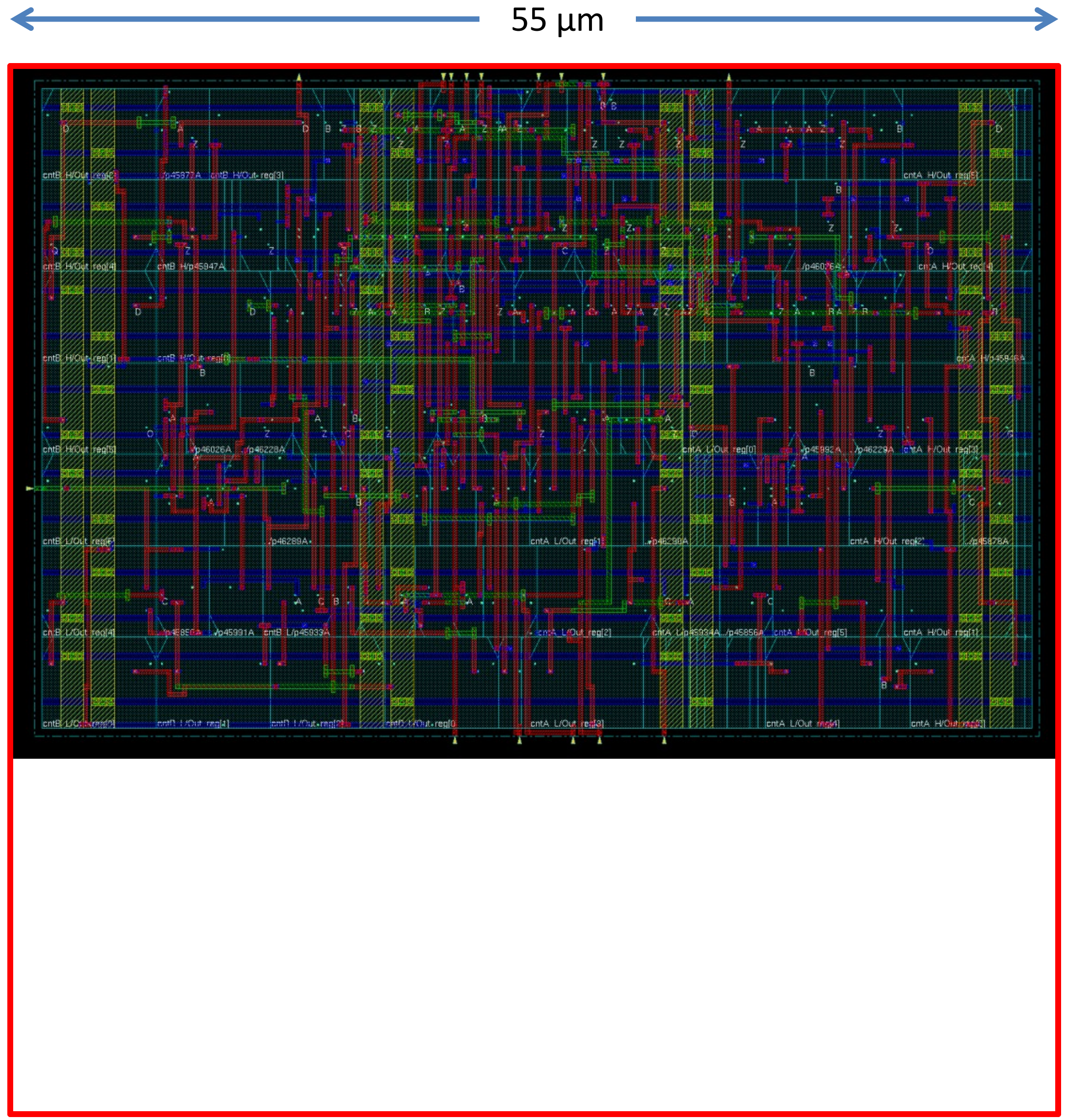
An high density low power 130 nm digital library

- The design of the Timepix3 goes in parallel with the Medipix3.2 design
- The Medipix3.2 redesign requires significant changes in the digital part of the pixel (designed as a full custom layout)
- Can we use CERN default standard cell 130nm library at the pixel level?
  - **Too big:** @CERN the default library has large cells since is targeted for ~800MHz !!
  - **Too much leakage power:** @CERN the default library is not low-power
- A custom made high density library (SC_130nm_XL) design has been done with the initial idea of using it in Medipix3.2 pixel but with a huge potential impact in later developments (Timepix3, Velopix…)
- Main actions:
  - Reduce cells height → We don't need big buffers (speed)
  - Keep all transistor small or minimum size (W/L=0.28/0.12)
  - ADD NV and PV layers → Low power transistors (no area penalty)

Medipix3 pixel counter (24 bits) + control logic

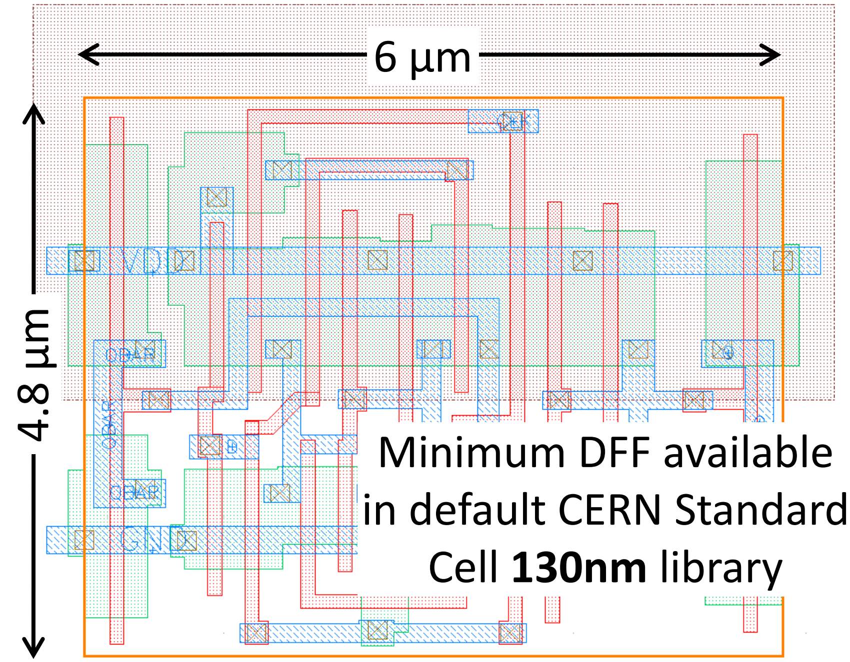
- Synthesized using the CERN IBM 130nm Standard Cell Library (CMOS8RF)
- Area is too big (52 x 33.6) → ~60% pixel area
- High static (leakage) power consumption:

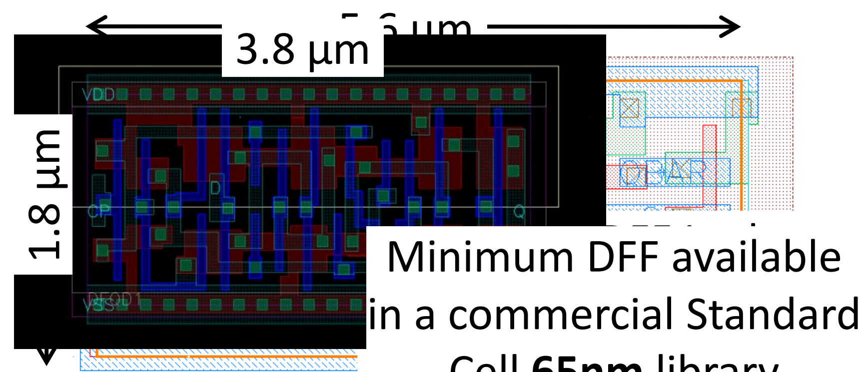
VDD	Temp	Leakage in cell	leakage In Chip
1.4 V	125 C	22.5 µW	**1.5 W !!!**
1.5 V	25 C	223 nW	**14.6 mW**
1.6 V	-55 C	470 pW	**30 µW**



SC_130nm_XL Library

- Row Height is fixed to 2.4 µm
- Well Tap library
- Maximum frequency <~350 MHz
- Low power transistors
- ~45 cells are available in the library (growing fast…)
  - No SEU registers (so far)
- Encounter Library Characterizer (ELC) has been used to fully characterize the library in different corners
  - Full Synopsis library
  - Verilog library
  - LEF files



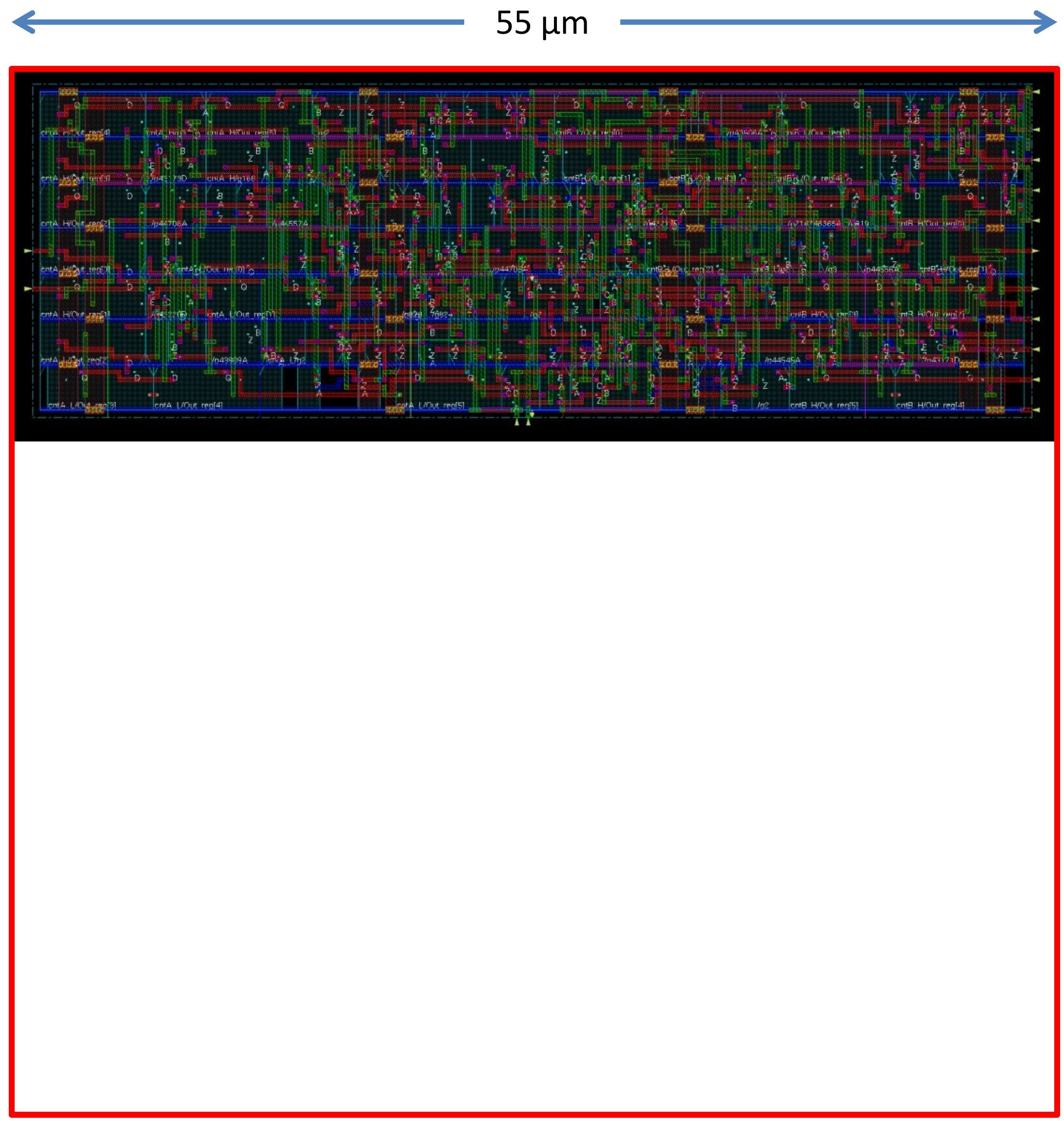


x4 smaller !!!

Medipix3 pixel counter (24 bits) + control logic

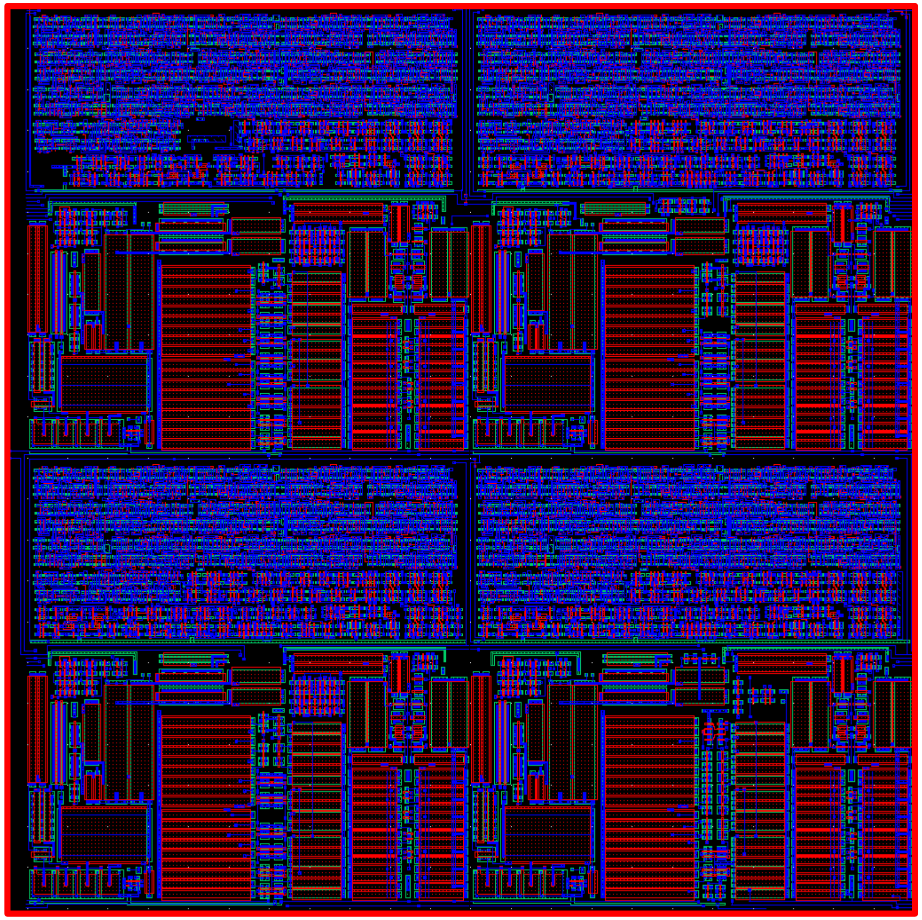
- Synthesized using the SC_130nm_XL library
- Area (52 x 16.8) → ~29% pixel area
- Low cell leakage power

VDD	Temp	Leakage in cell	leakage In Chip
1.5 V	25 C	2.5 nW	**163 µW**
1.2 V	25 C	1.15 nW	**75.3 µW**

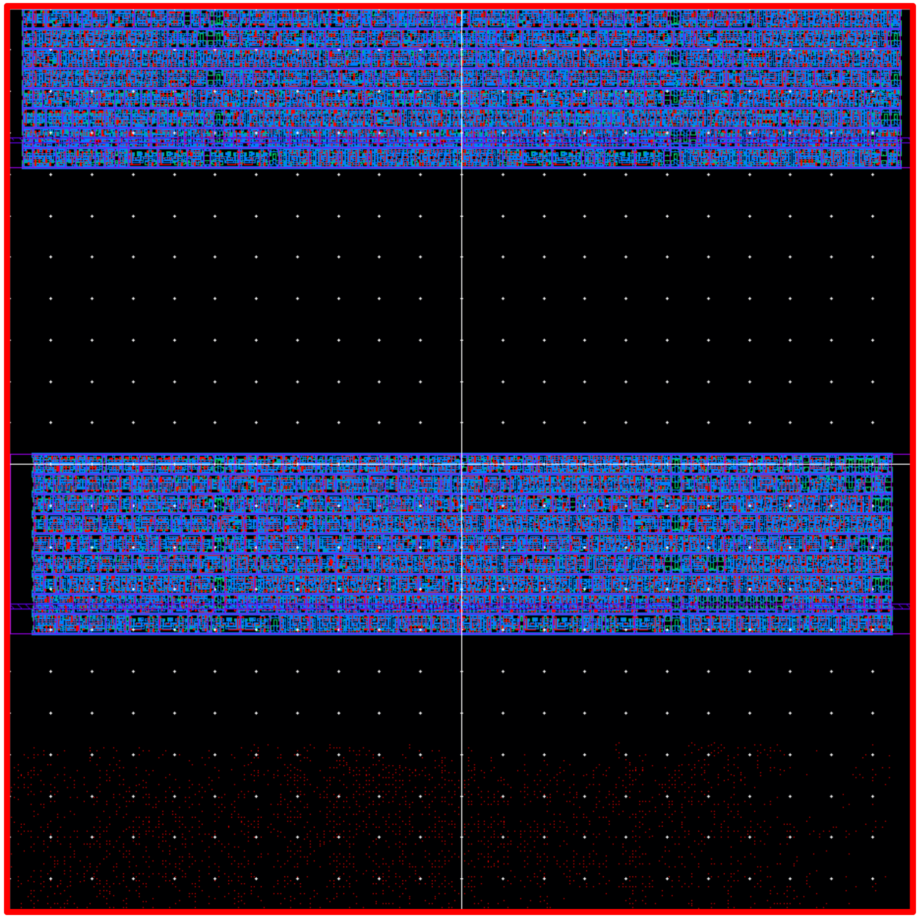


Comparison between old and new counter

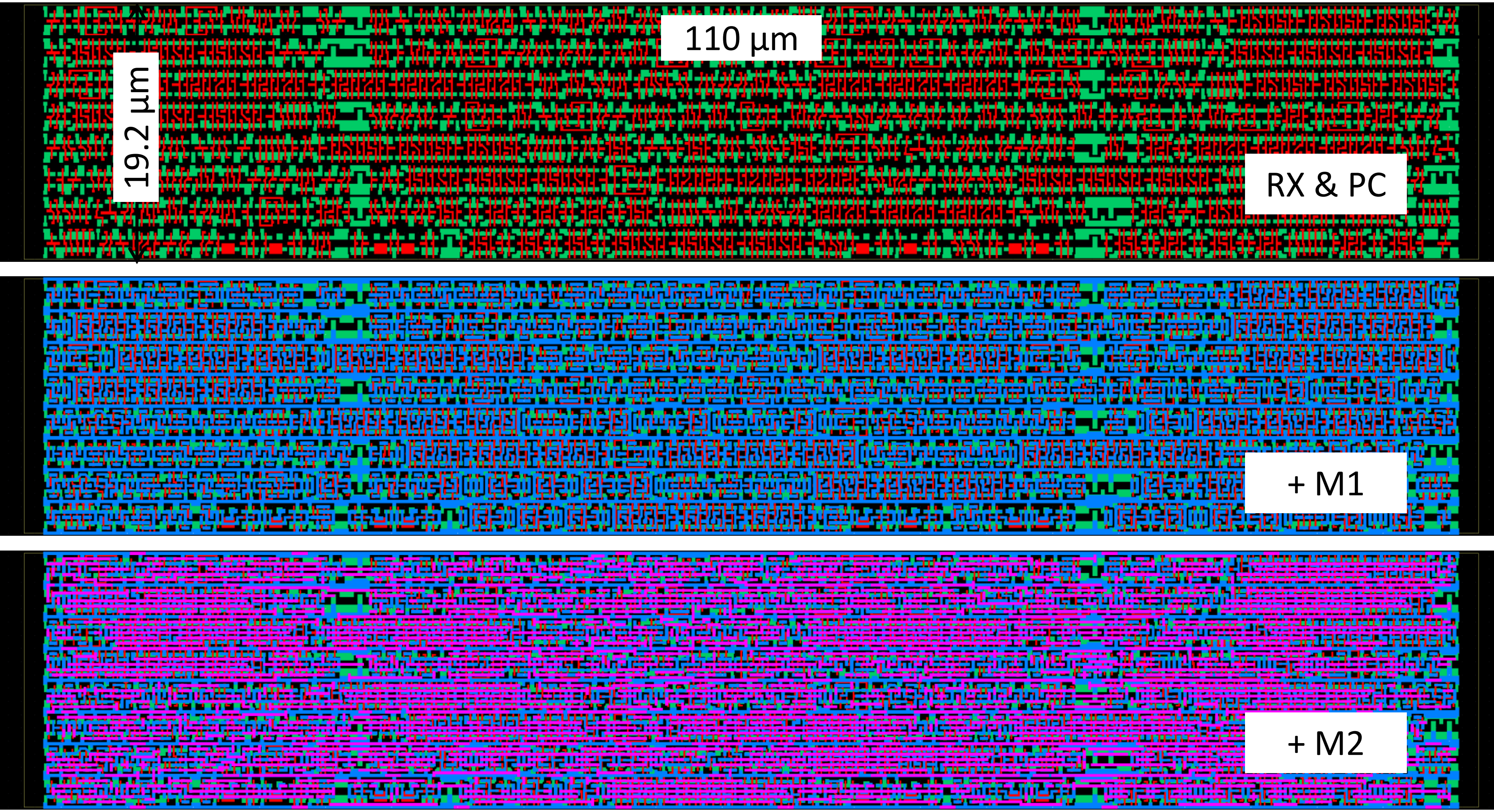
Medipix3.0 (2009)



Medipix3.2 (2011) using SC_130nm_XL



Medipix3.2 counter using SC_130nm_XL library



CONCLUSIONS

Conclusions

- The Timepix3 will be the next chip in the Medipix family
  - TOT and TOA simultaneously
  - Sparse and data driven readout
- The use of a new high density and low power digital library helps to optimize the pixel digital area
- Submission of the Timepix3 chip is expected by beginning of 2012