Digital SiPM array for photon detection in next generation Xenon based rare event search experiments

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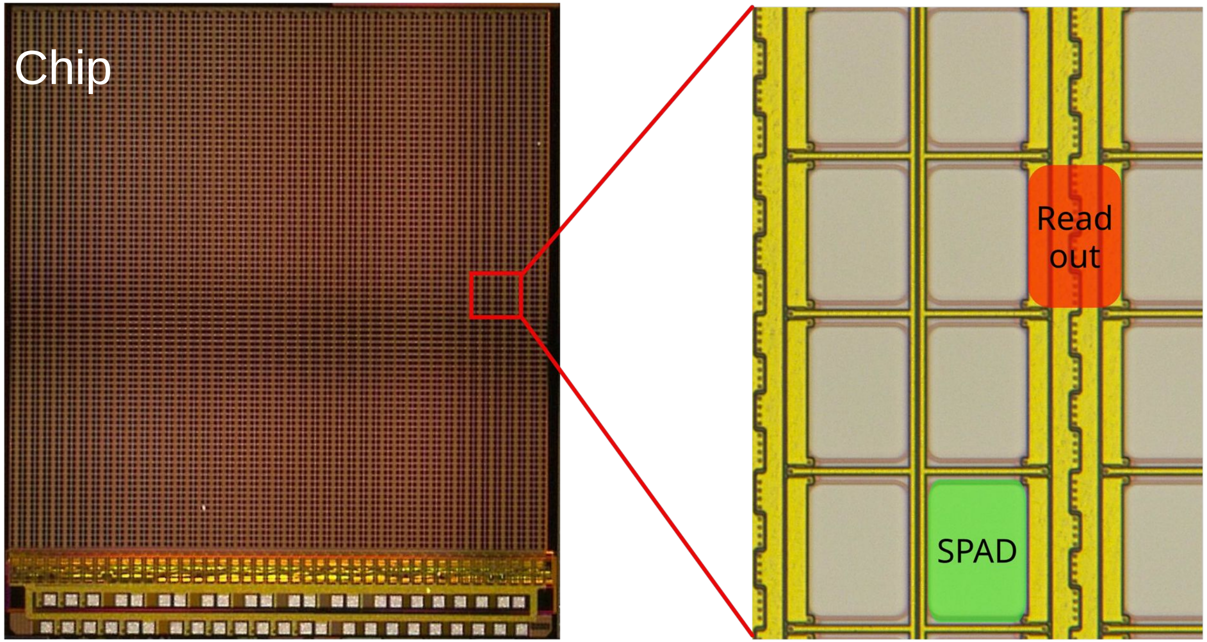
Workshop on Xenon Detector 0νββ Searches: Steps Towards the Kilotonne Scale

SLAC 27.10.2023

Digital SiPMs

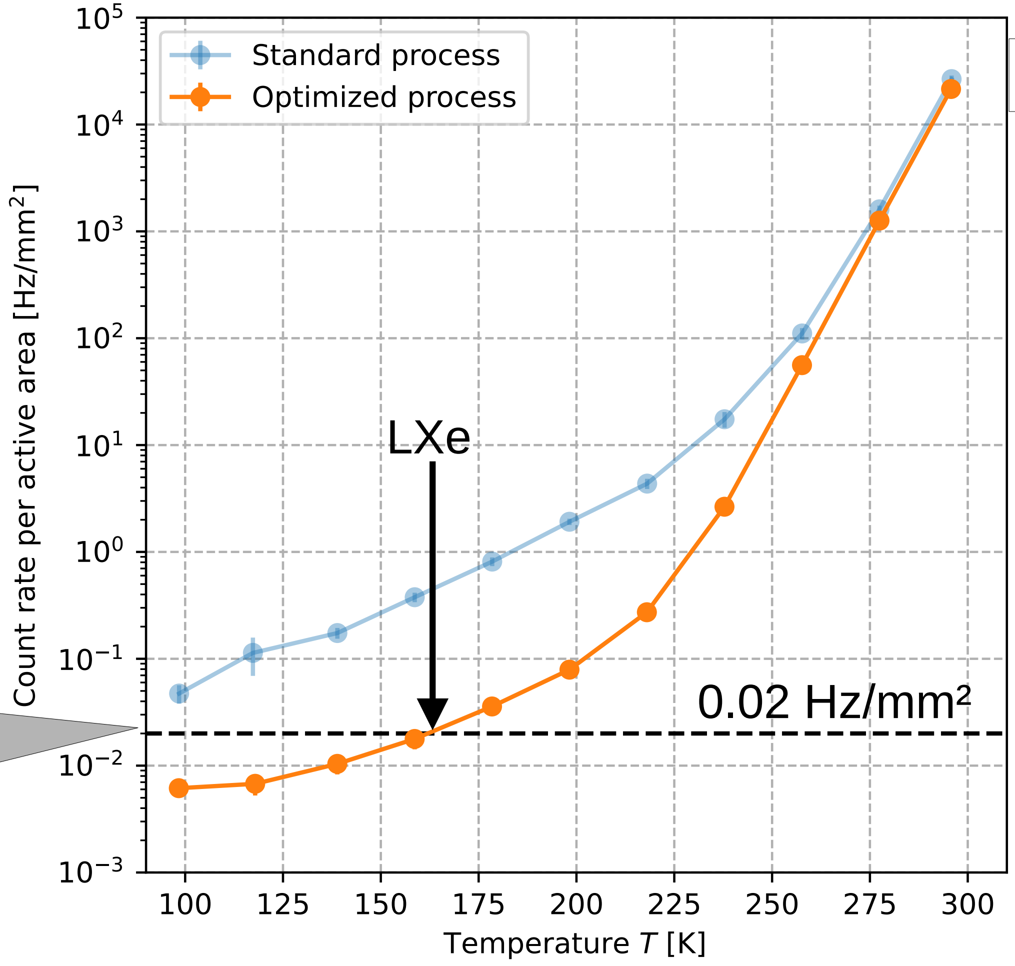


SPADs (single photon detector) and their CMOS readout electronics are manufactured on one silicon chip:

- Fully integrated system with purely digital output signals and simple mechanics
- No power consuming ADCs needed and only few external passive components → low radioactivity
- Noisy (‚hot') SPADs can be electronically turned off → much lower overall DCR!
- Lower fill factor and higher noise (compared to standard SiPMs) due to electronics(?)

SPAD Quality

Dark Count Rate



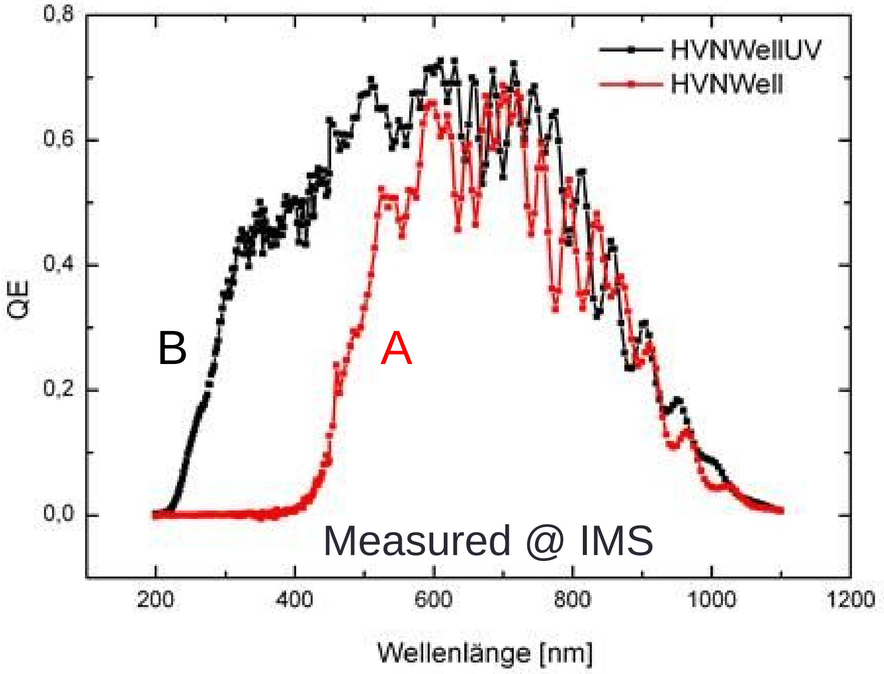
RT: ~25 kHz/mm²

Our Manufacturer IMS improved the DCR at low T more than an order of magnitude!

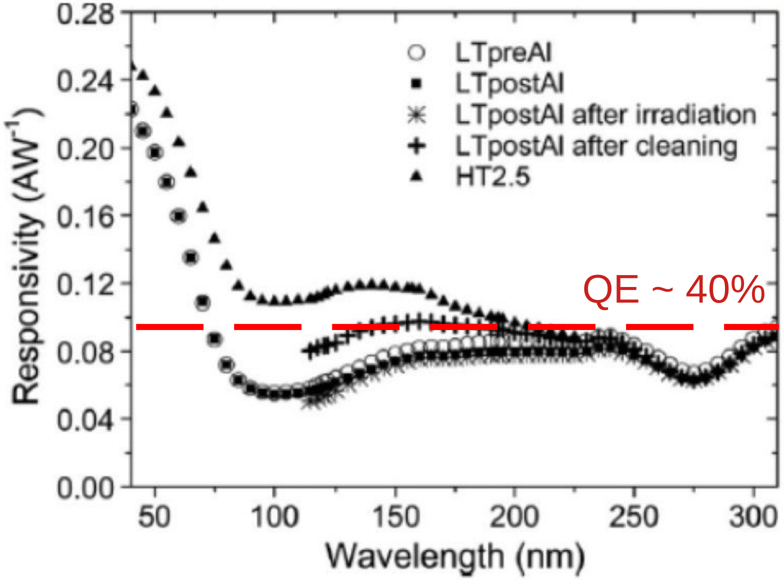
Quantum Efficiency

- IMS has two established processes which offer excellent QE for visible (A) and UV light (B, UV transparent passivation)
- SPADs can be operated with wavelength shifters

- Deep UV sensitivity can be done but needs new processes. IMS clean room is currently under structural changes.
  → Production is still delayed (starts now)



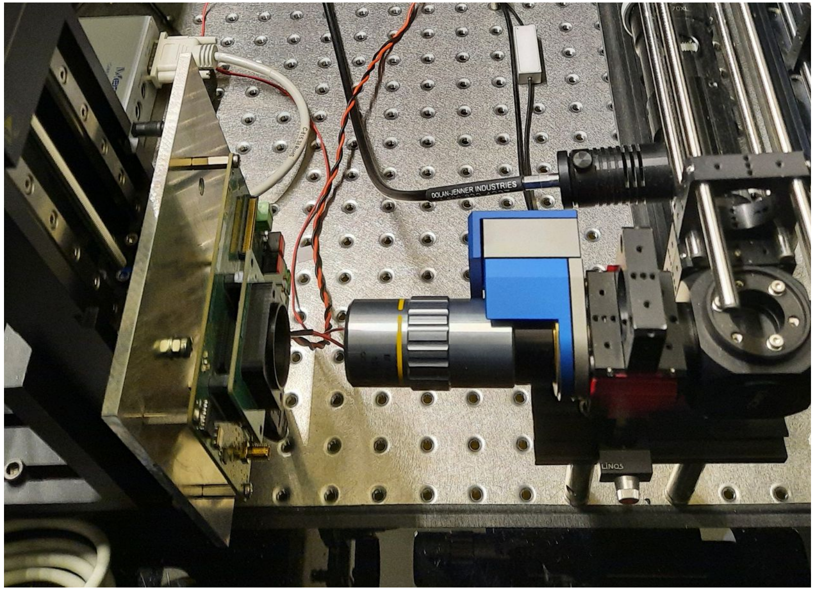
Responsitivity of photodiode(!) with PureB

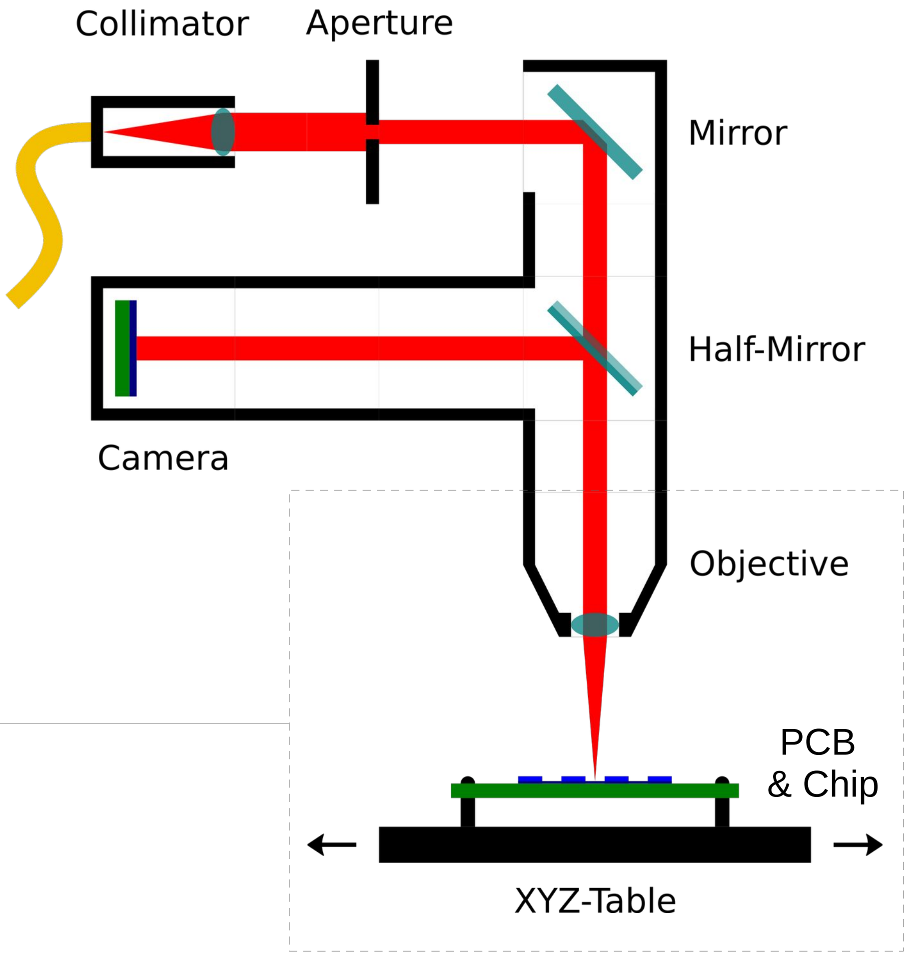


Nanver, Lis K. IEEE Journal of Selected Topics in Quantum Electronics, 20(6):306-316, 2014 QE Estimate: IMS private communication

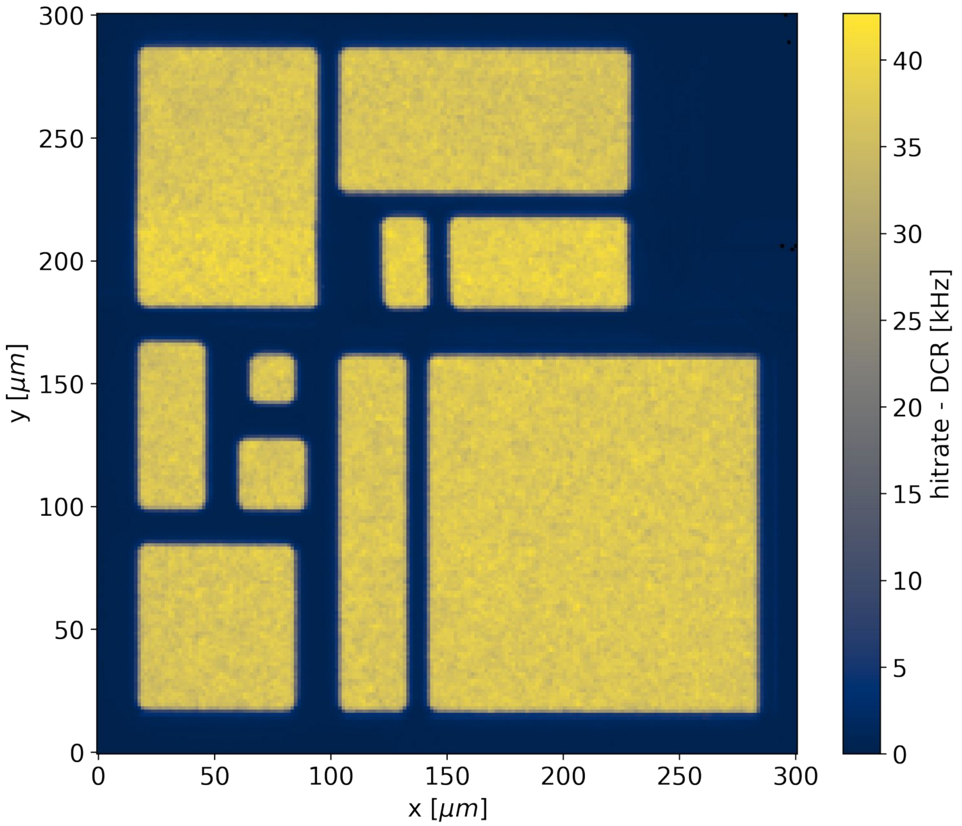
Laser Setup

- Our existing laser setup was reactivated and optimized
- Sensor scan in XYZ direction with < 1 µm steps and Laser spot of < 5 µm.
- We scanned our Digitial SiPMs and now started to scan various standard SiPMs for comparison



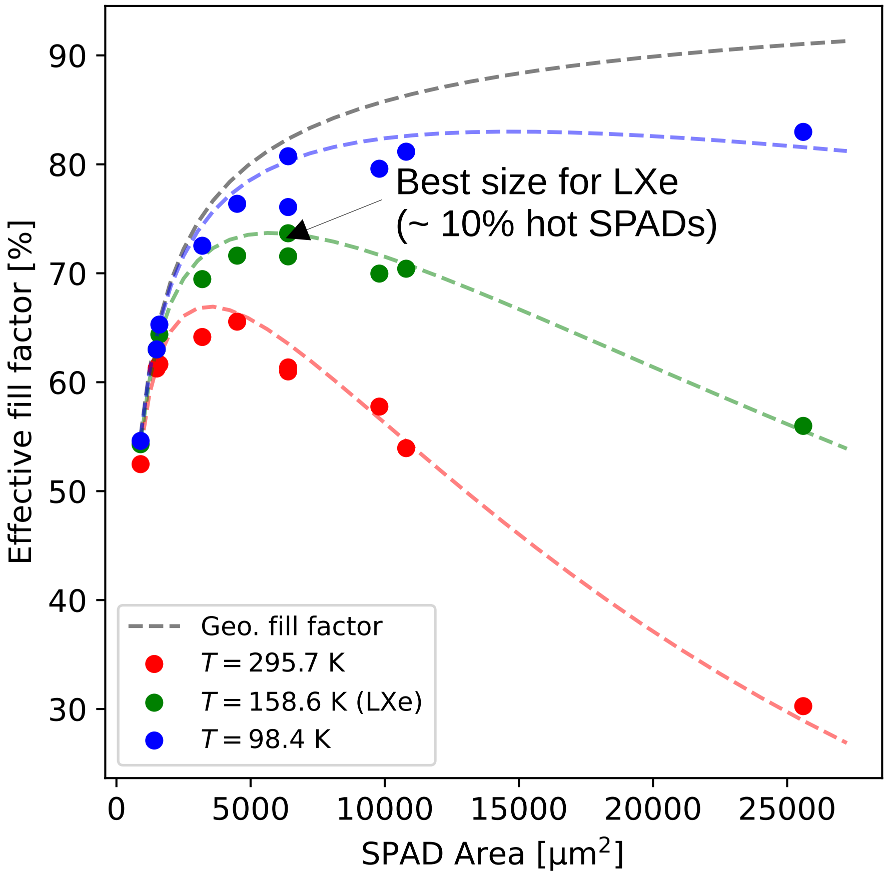


Spatial Response and Active Region

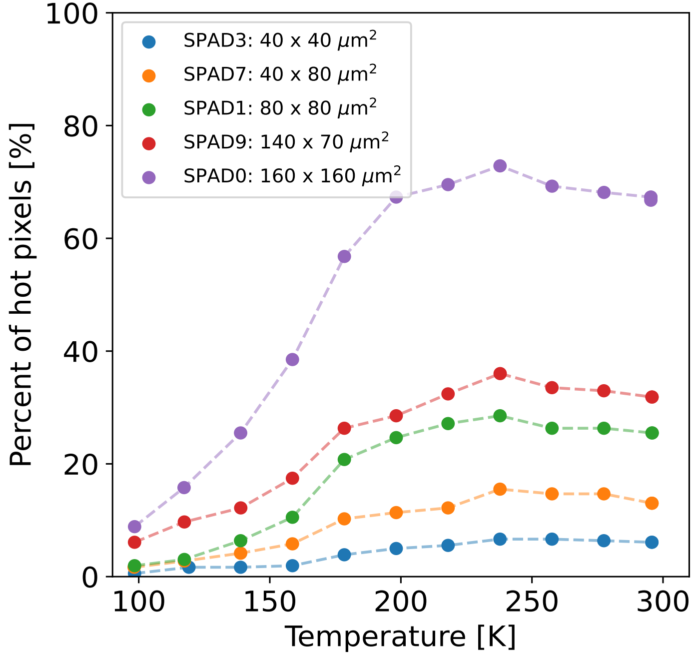


- Scan of DARWIN Test chip, hosting SPADs of different shapes and sizes. (DCR subtracted)
- All SPADs show a very homogeneous spatial response
- Measured active area of all SPAD shapes and sizes is in good agreement with the calculated active area.
- Width and length of actual SPAD is about 2 µm smaller than the design.

Hot SPADs and Fill Factor



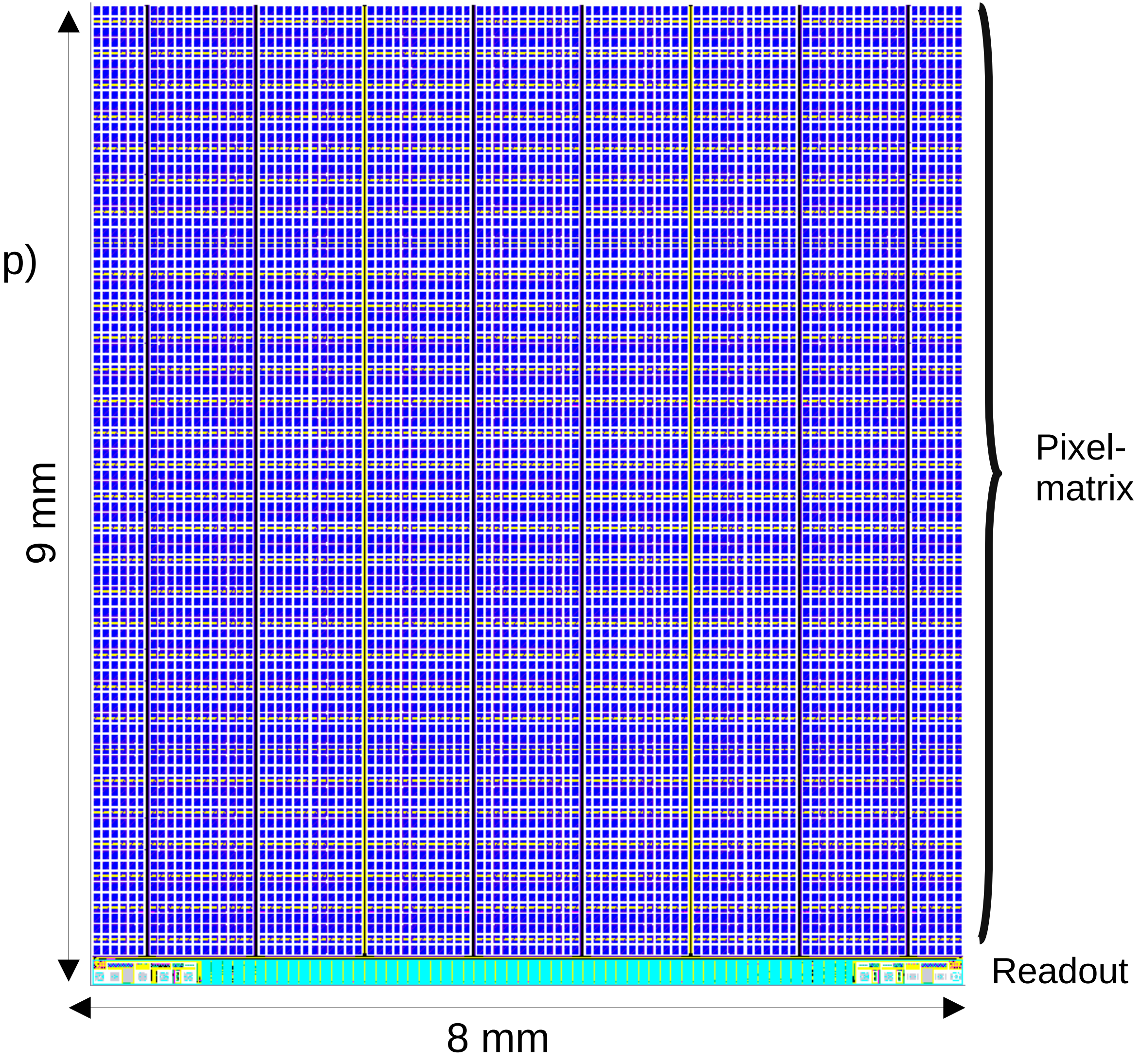
- Hot SPADs have enhanced noise and have to be turned off → reduction of active area / FF
- Fraction of hot SPADs increase with SPAD size, but decreases at low temperatures
- Effecitve fill factor = geo. FF x (1 - fraction of Hot SPADs)



High fill factor digital SiPM Array

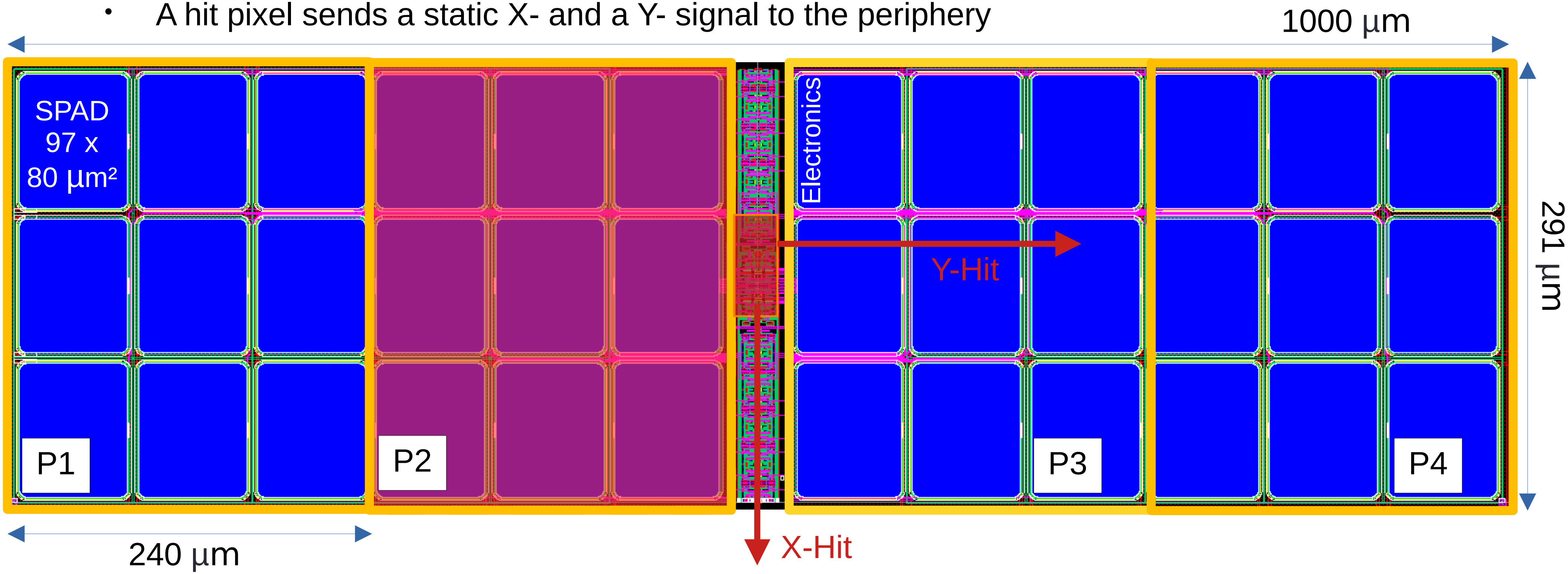
DARWIN Array

- Development triggered by DARWIN a LXe dark matter search experiment (We are part of the light sensor R&D group)
- Submission done this month!
- Chip area ~ $72 mm^2$
- Fill factor is ~77% (incl. edges etc.)
- Matrix of 16x60 Pixels
- Readout offers:
  - Spatial resolution (x/y ~ 300µm)
  - Event time-Stamps (Δt ~ 10ns)
  - Serial data output (low number of pads)
- Daisy chaining of up to 64 chips to build detector modules

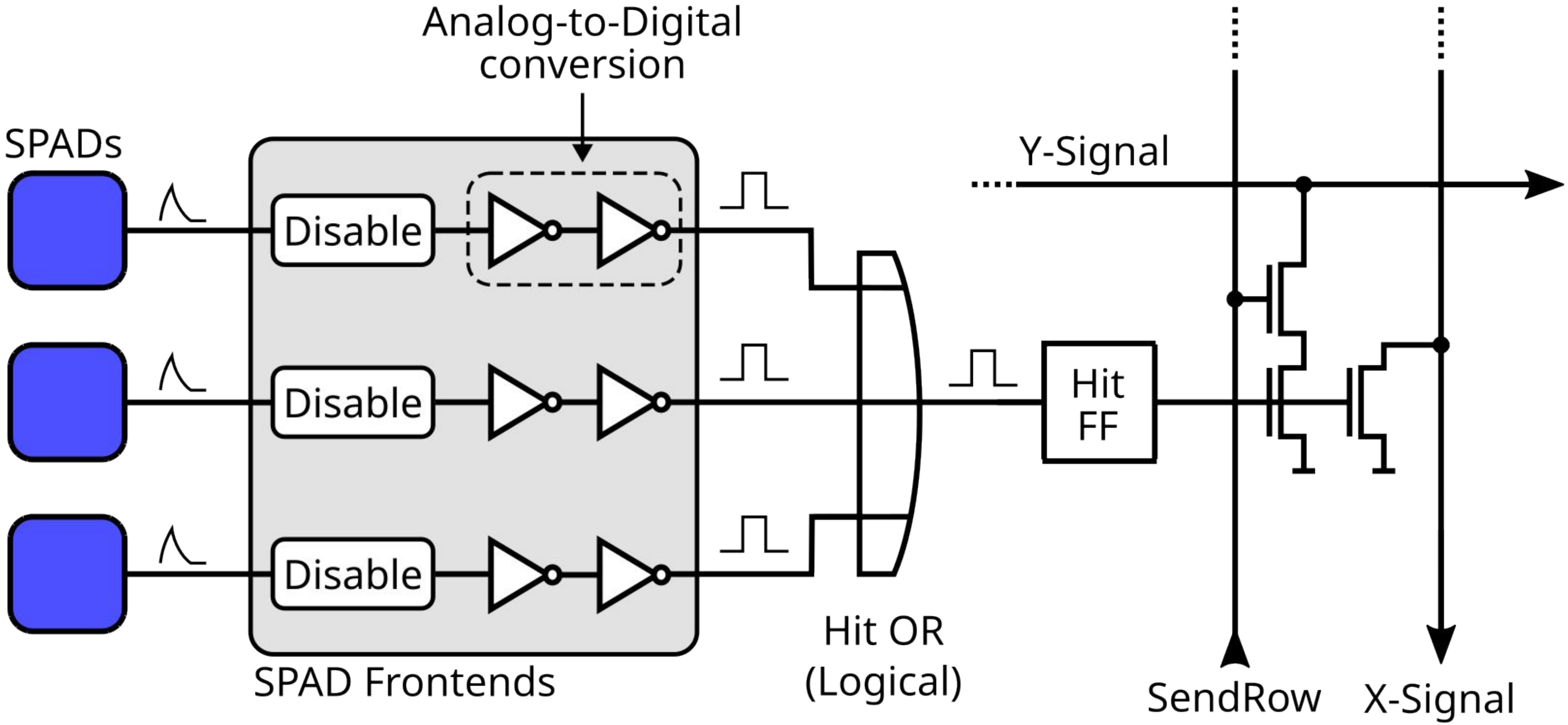


Pixel

- Pixel comprises 9 SPADs. Each SPAD can be disabled if noisy. Hit = Logical OR of all SPADs → SPADs of a Pixel act as **ONE** large SPAD
- Layout: Readout electronics of 4 Pixels are placed in one common block:
  - Mask Bits, Test Inject, FlipFlop to store Hit
  - A hit pixel sends a static X- and a Y- signal to the periphery

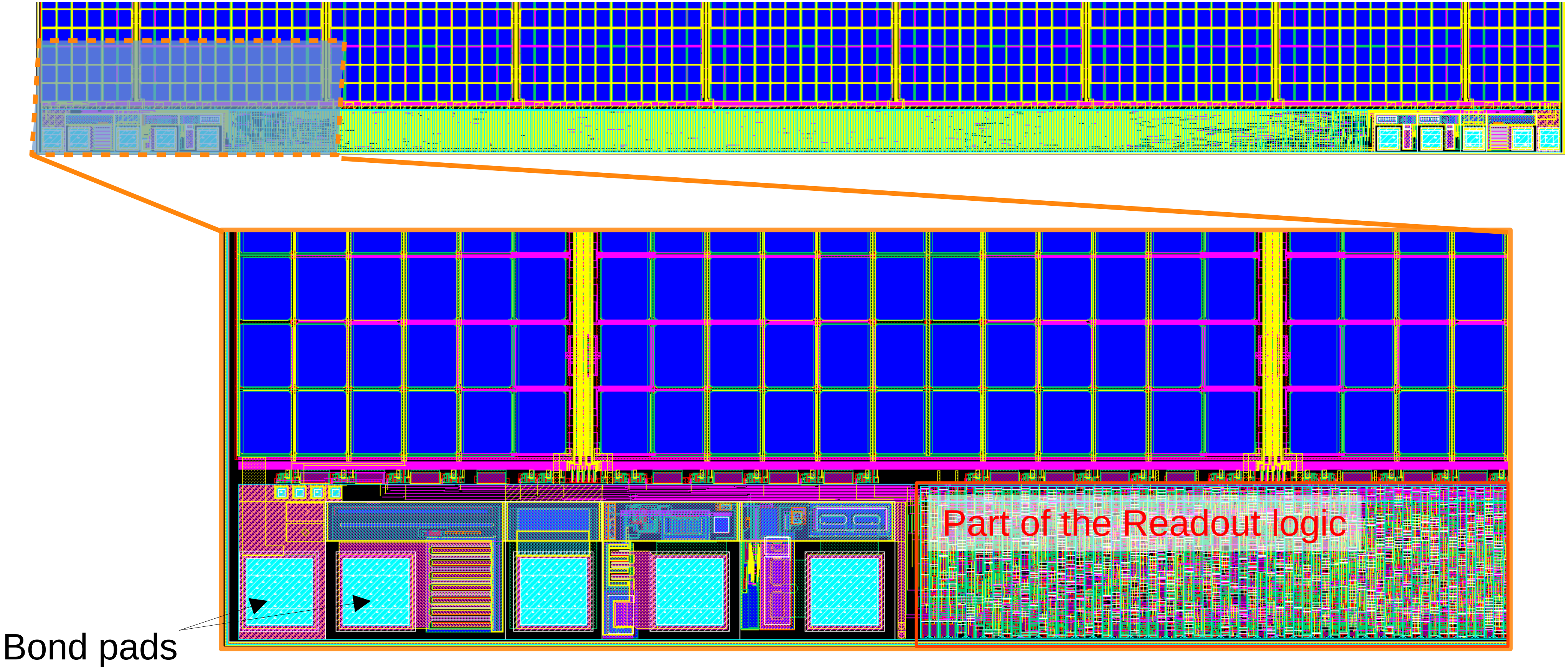


Pixel – Electronics



Readout

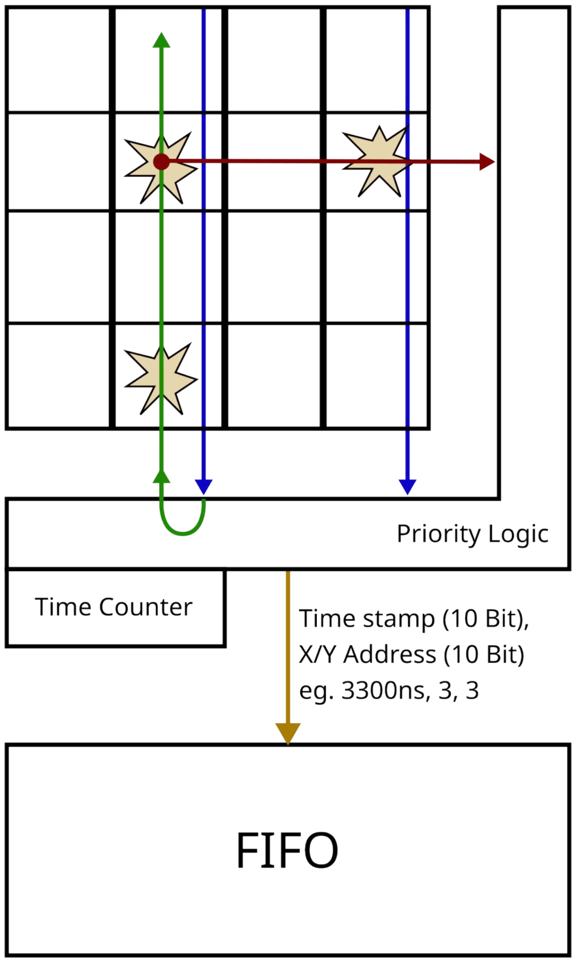
- Data Driven Logic “squeezed” between bond pads. Fully synthesized from HDL-code. (Low power consumption, which scales roughly linear with photon occupancy)



Hit Finding

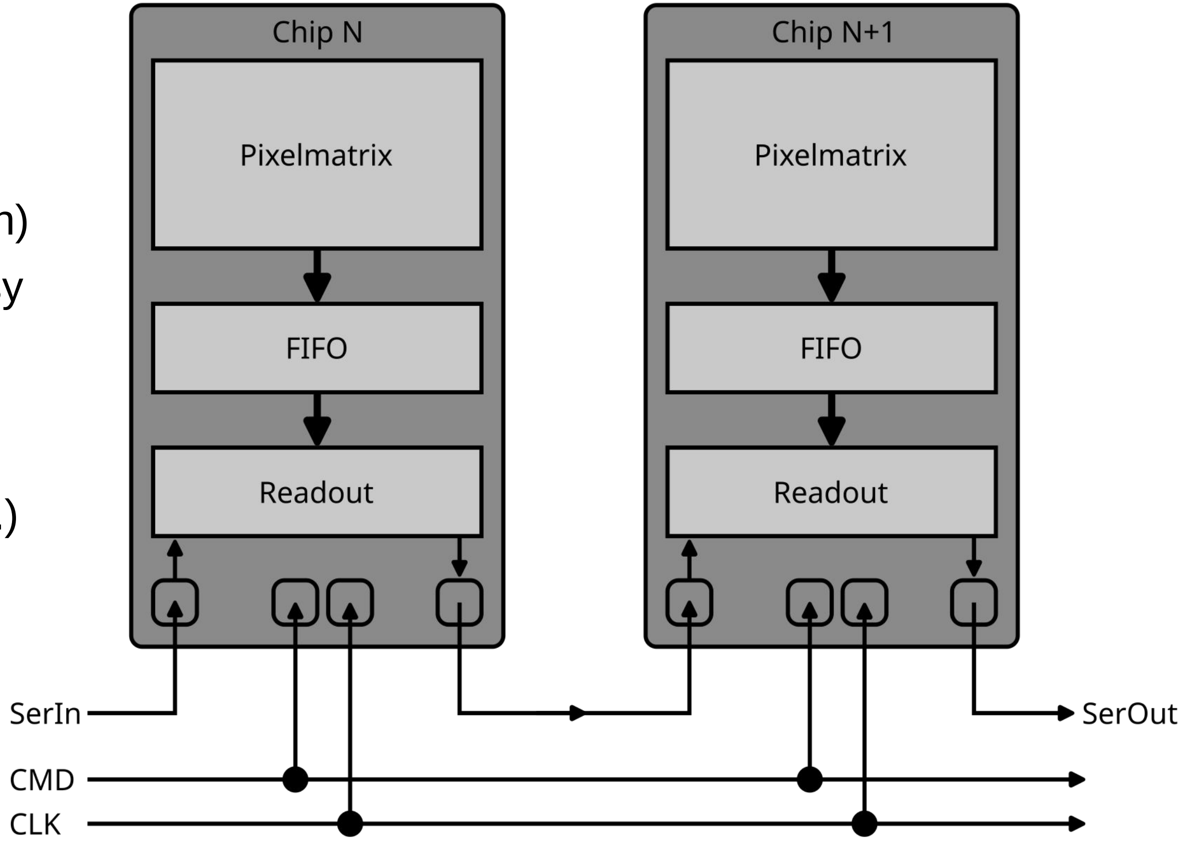
The chip delivers X-Y-T information for EACH hit macropixel:

- All hits are flagged to periphery via X-Y-signals
  Multiple active X-Y-signals are possible for multiple hits!
- A priority readout logic
  - Chooses one column with active X-signal (prioritizes highest X address)
  - Finds *the first* associated Y-signal
  - converts X/Y to an (binary) address
  - assigns a column wise time stamp (1/(2*CLK) resolution, recorded when first(!) X-Signal of column arrives.)
  - stores the hit in an on-chip FIFO (32 words)
- Scan continues until all columns are processed
  - 60 ns / Hit in same column
  - 160 ns / Hit in different column @ 50 MHz chip clock

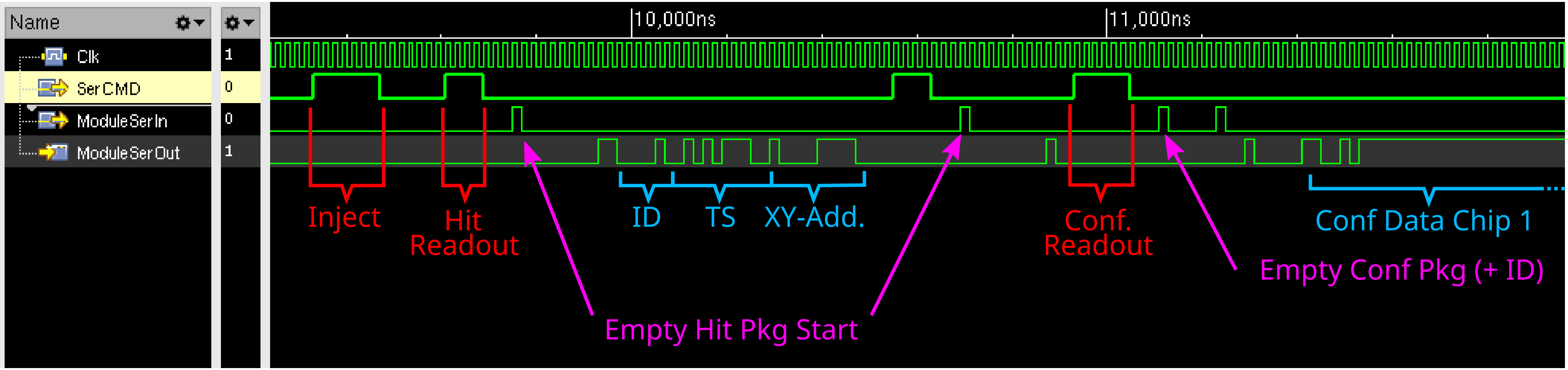


Data Readout

- FIFO is emptied on one serial line
  - 6 Bit ID (unique for each chip)
  - 10 Bit XY Address
  - 10 Bit Time stamp (20.5 us epoch)
- Hit data can propagate through a daisy chain of (up to 64) chips.
- Default clock speed is 50 MHz
- One global CMD signals controls everything (config, reset, readout, etc.)
- 7 chip signals (10 Bond Pads):
  - 4 digital, as shown
  - 2 supply (power, ground)
  - 1 HV for SPAD



Chain Simulation



Simulation of a chain of 3 chips:

1) Only one pixel (7/33) on chip 2 has been activated (not shown)
2) Electrical injection is performed in all chips.
3) Two hit readout CMDs are given. Since only one pixel is active, only one bit string is send.
4) Configuration register of chip 1 is read. (not all bits are shown)

Rate Limits (@ CLK = 50 MHz, conservative)

Continuous rate of photons:

- Sending hit to FIFO takes 160 ns.
- Readout of 26 Bit hit data requires 520 ns

→ rate limited by readout speed

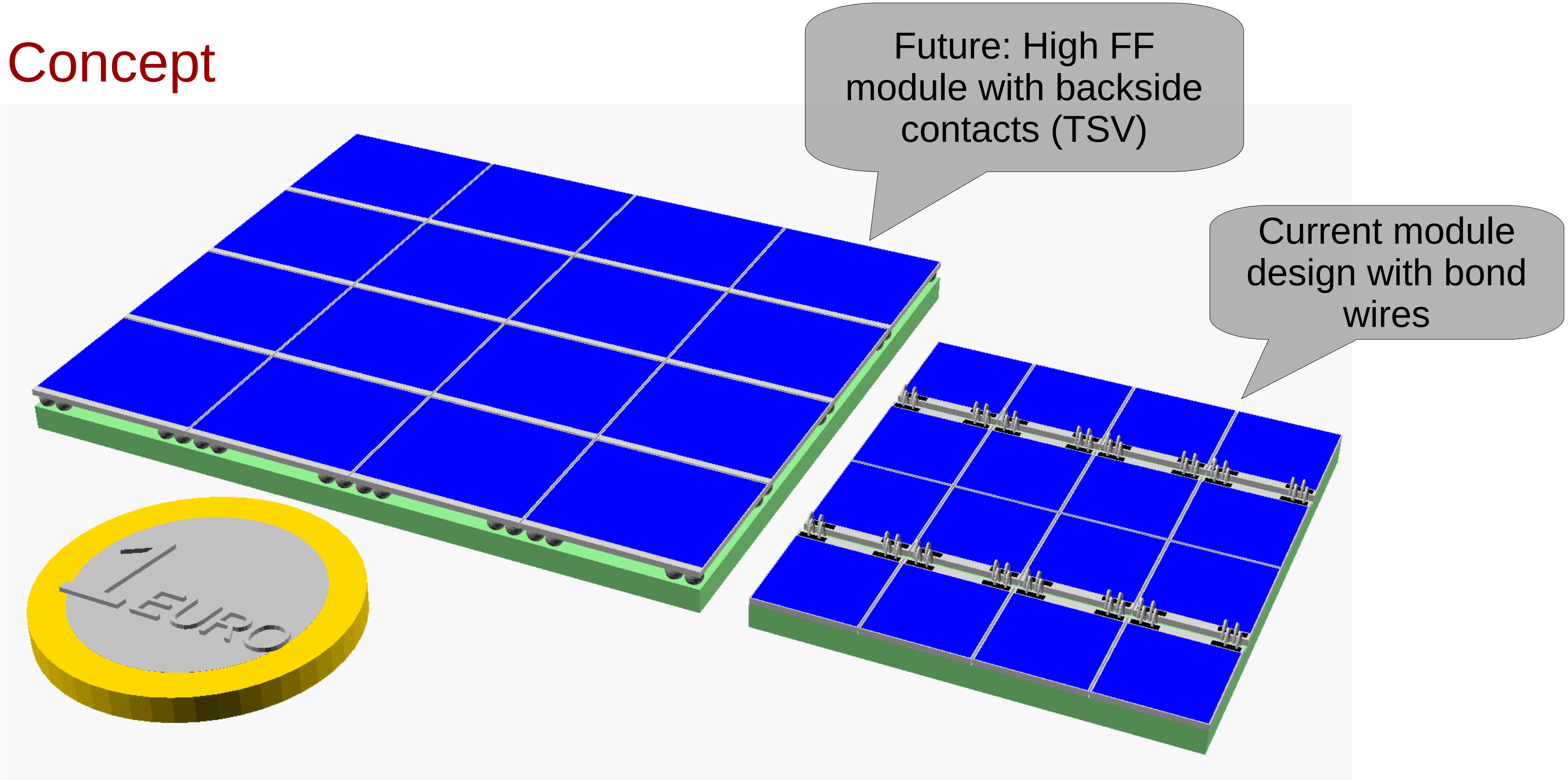
  - ~ 1.8 Mevents / chain / s
  - **~ 1.6 kEvents / mm^2 / s** (@ 16 chips / chain)

Instantaneous burst of photons:

- Hits remain stored in macro pixel *until they are read out!* (Serial Readout can take long)
  - (Successive hits in same column get wrong time stamps)
- Pileup due to pixel size (0.07 mm^2 ~ 14 pixels/mm^2)
- Example: For **1 hit/mm^2** in all chips, **full readout requires 600 μs** (@ 16 chips / chain)

If the photon occupancy surpasses chain readout speed or the macro pixels are occupied when the next burst is happening **photons are lost** (Currently simulations are done to quantify this)

Module Concept



- Module with 16 – 64 chips. Low activity substrate (eg. silicon!) as support structure and for electrical contacting. No further passive components are needed.
- Option: Bond pads can be contacted by Through Silicon Vias (TSV) → increase module fill factor. Test implementation of TSVs is planed!

Next Steps

- Test of DARWIN Array
  - Will receive the chips from IMS in March 2024
  - Will be produced with standard QE and DCR :-(
  - Building a small 2 x 2 Chip module

- Production of the deep UV sensitive SPADs starts (after a long delay) at IMS
- A DSiPM array will be operated in liquid Xenon (cooperation with the KIT and University of Freiburg, we start in October 2023!)
- Finalize Fill Factor measurement for standard SiPMs (Robert has tested a Hamamatsu and FBK SiPMs)
- Radio-purity test → IMS is gathering a larger amount of samples
- Simulation of rate limits and photon loss scenarios in DARWIN TPC environment
- SPAD light emission studies

Thank you.

For further questions contact me:

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