24 th iWoRiD International Workshop on Radiation Imaging Detectors

# X-ray Detectors for LCLS-II with real-time information extraction: the SparkPix family

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SLAC NATIONAL ACCELERATOR LABORATORY · Argonne NATIONAL LABORATORY · POLITECNICO MILANO 1863 · Stanford University · U.S. DEPARTMENT OF ENERGY

# LCLS-II & LCLS-II-HE: revolutionary tools for X-ray science

- LCLS-II will be the first XFEL to be based on continuous-wave superconducting accelerator technology
- Continuous repetition rate of 1 MHz, with photon energies between 250 eV and 12 keV

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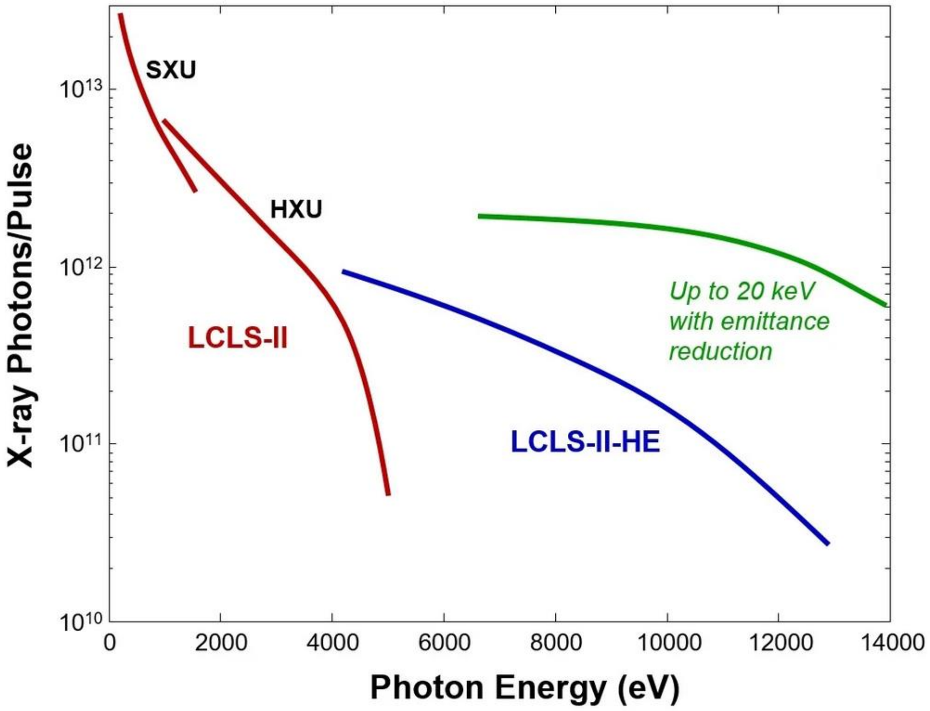
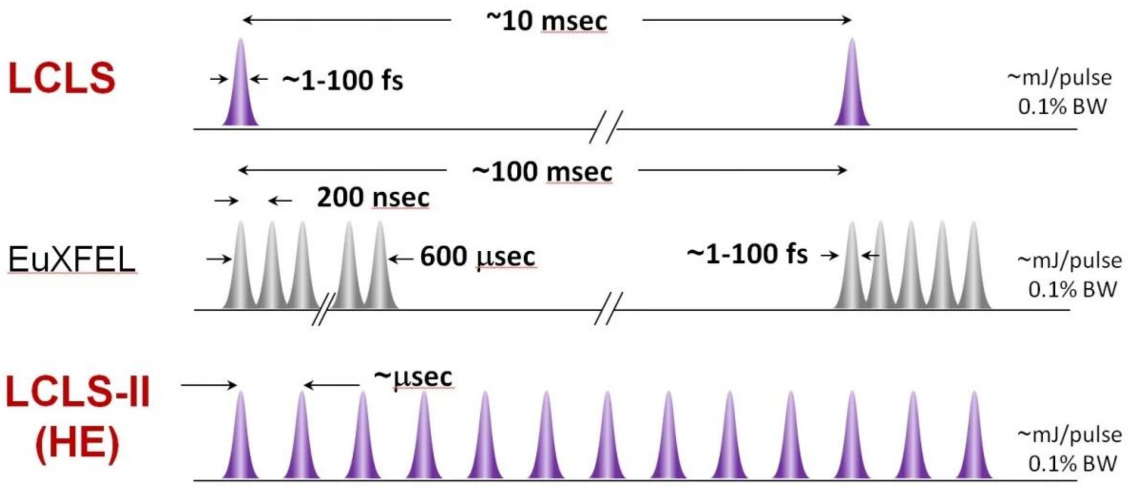


# LCLS-II: the data challenge


- Moving data through the detector layers (ASIC, FPGA, DAQ) is not the only challenge
- **Data analysis needed** during data collection:
  - Must be able to get **real-time feedback** and the quality of data-taking **(~1 sec)**
  - Must be able to get feedback about the quality of the acquired data with a latency lower (~1 min) than the typical lifetime of a measurement (~10 min)

**On-the-fly data reduction:** Data Reduction Pipeline starts in first detector layer with "intelligence" = ASIC



See also *J. Thayer, Massive-scale Data Analytics at the Linac Coherent Light Source, CHEP 2023*

# SLAC long-term X-ray detector development plan

## Bigger, Faster, Higher resolution and Higher Energies

With goals built into projects progressively meeting science priorities and requirements

### ePixUHR$_{35kHz}$ (2019-2027)

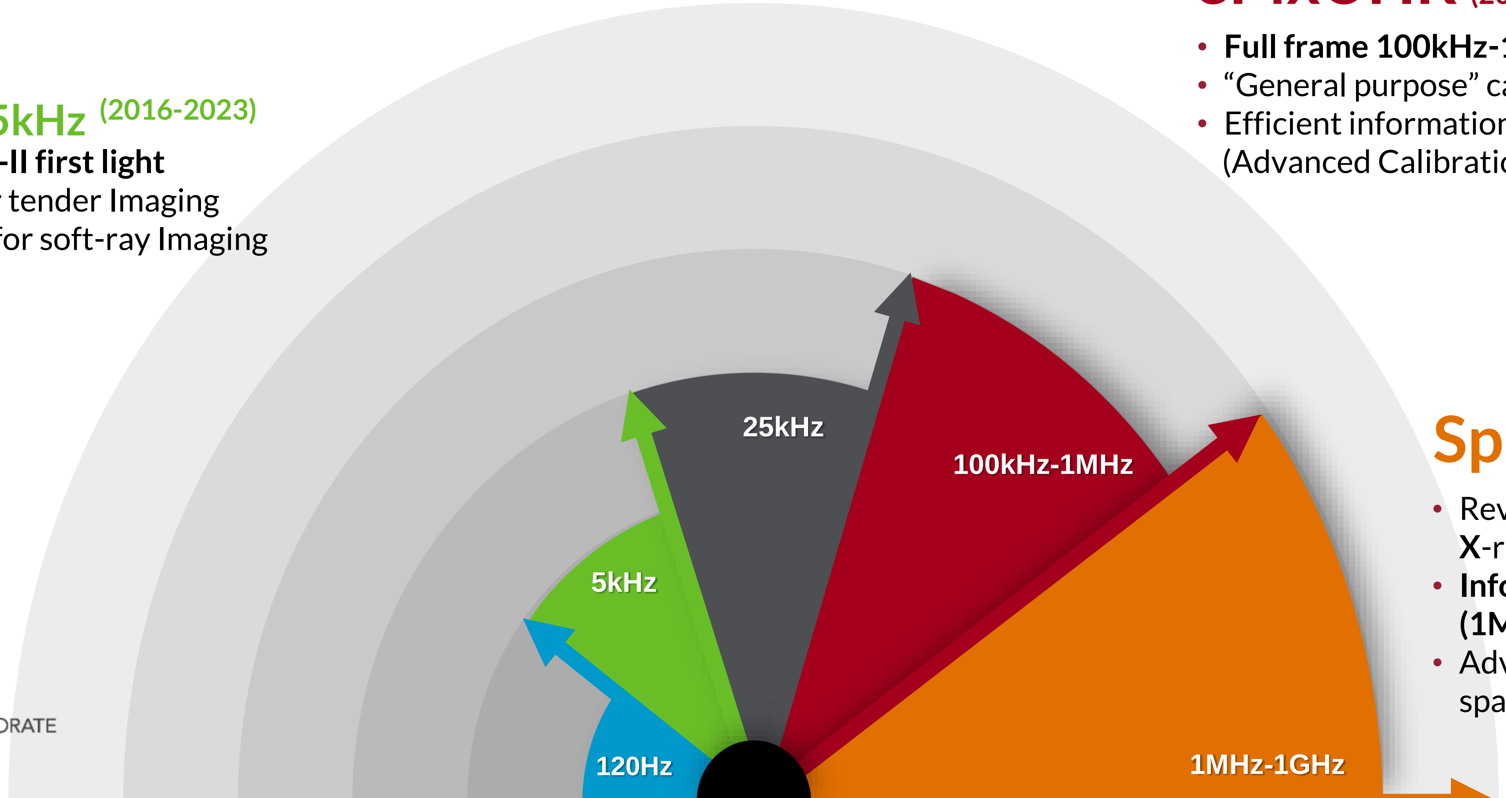
- **Full frame 35kHz for HE first light**
- Sensors for hard X-rays

### ePixUHR (2019-2029)

- **Full frame 100kHz-1MHz**
- "General purpose" cameras
- Efficient information extraction (Advanced Calibration / Edge-ML)

### ePixHR$_{5kHz}$ (2016-2023)

- **5kHz for LCLS-II first light**
- ePixHR10k for tender Imaging
- ePixHR250M for soft-ray Imaging




### SparkPix (2020-2027)

- Revolutionary **E**xperiment **S**pecific **X**-ray **C**ameras
- **Information extraction at full rate (1MHz CW, 3GHz burst)**
- Advanced features (triggering, sparsification, zero suppression etc.)

### ePix (2013-2018)

- **In use at LCLS**

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Tomorrow's 2 PM

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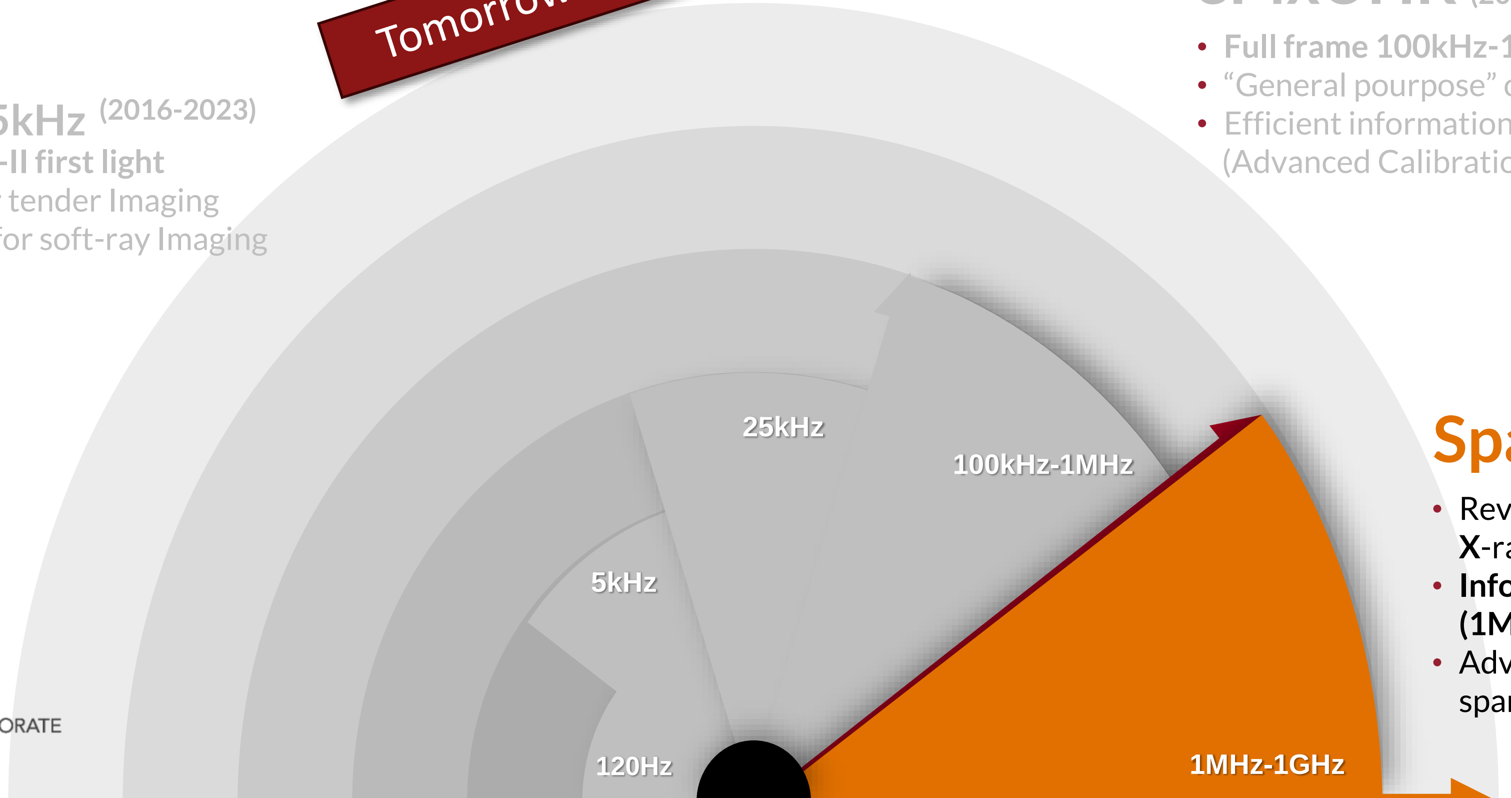


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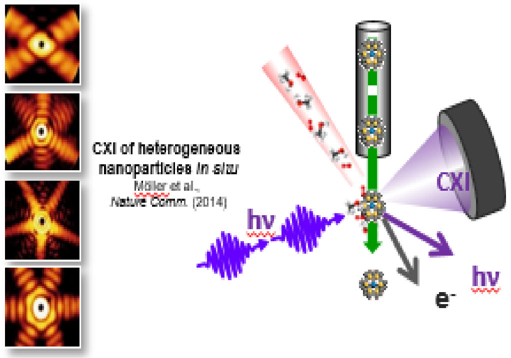
# The science case for detectors: high-rate and versatility

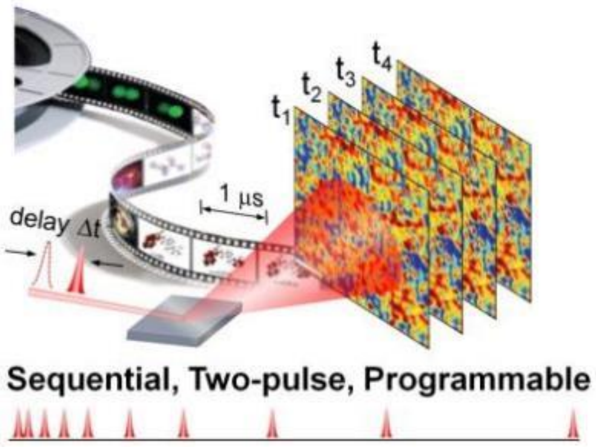
## Require full frame 100 kHz detectors




**Imaging non-identical objects**

e.g. Heterogeneity of functioning nano-catalysts

## Require 1 MHz detectors Sparse Data




**Stochastic Dynamics**

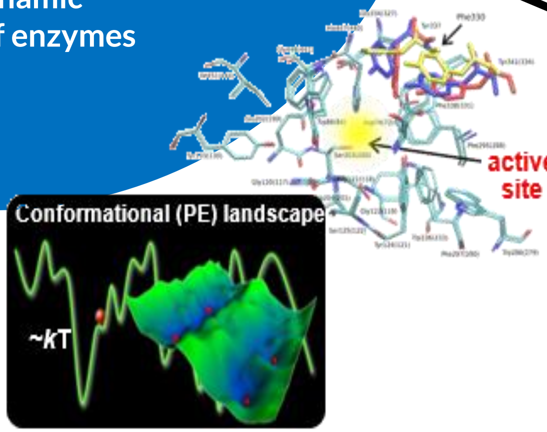
e.g. Glass transition, charge fluctuations in quantum materials

XPCS, XSVS

**“Rare Events”**

e.g. Dynamic function of enzymes

## Require 1 MHz detectors Event Driven



# SparkPix family

## Four different pixel detectors in SparkPix family (currently):

| | Front-end | Information extraction | Frame-rate |
|---|---|---|---|
| SparkPix-ED | energy | triggering | 1 MHz / 100 kHz CW |
| SparkPix-RT | energy | data compression | 100 kHz |
| SparkPix-S | energy | sparse readout | 1 MHz |
| SparkPix-T | timing | sparse readout | 1 MHz |

# Energy + triggering

# SparkPix-ED

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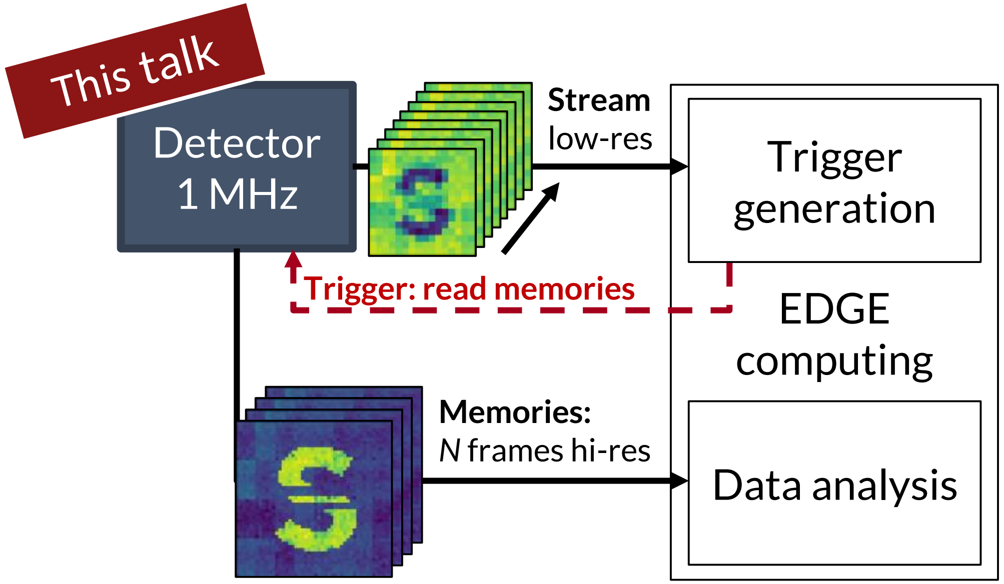
# SparkPix-ED: science driver & concept




**Rare events in X-ray scattering experiments**

- **Science case:** capture interesting events happening at random, stochastic times that make their observation difficult
- **Requirements:** record *N* high-resolution images at closely spaced times around the rare event

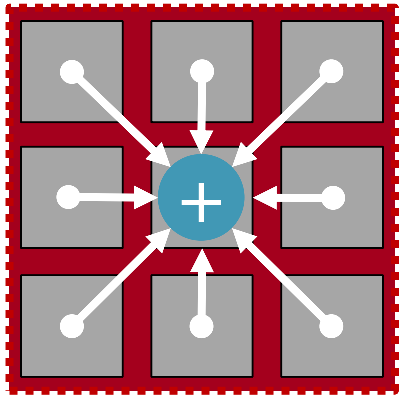
**Operation:**

1. Low-resolution images are continuously sent to the EDGE computing layer @ 1 MHz
   Meanwhile, *N* images are continuously recorded & stored in the detector in a ring-buffer
2. EDGE computing layer continuously analyzes data for rare events, then generated a trigger
3. The trigger starts the readout of the high-res *N* images recorded around the event of interest



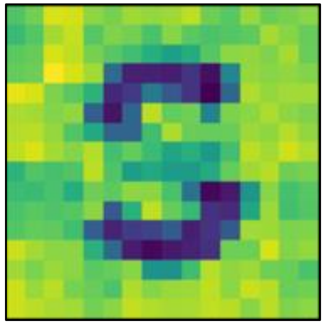
L. Rota *et al.*, "SparkPix-ED: a readout ASIC with 1 MHz frame-rate for rare event experiments at LCLS-II", IWORID 2021

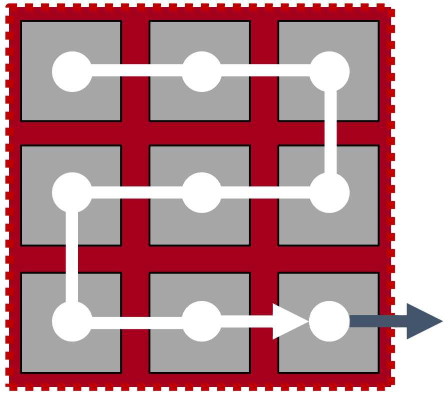
# MHz mode



## Fast read-out to triggering layer: 1 MHz stream

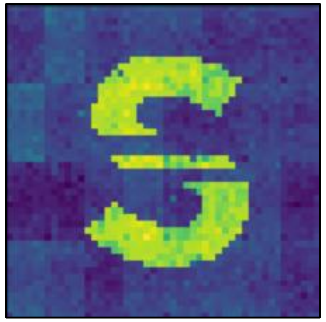
- Sum signal of 9 pixels, resulting in a SuperPixel (SP) of 300*300 μm$^2$
- Sum operation reduces SNR by √9



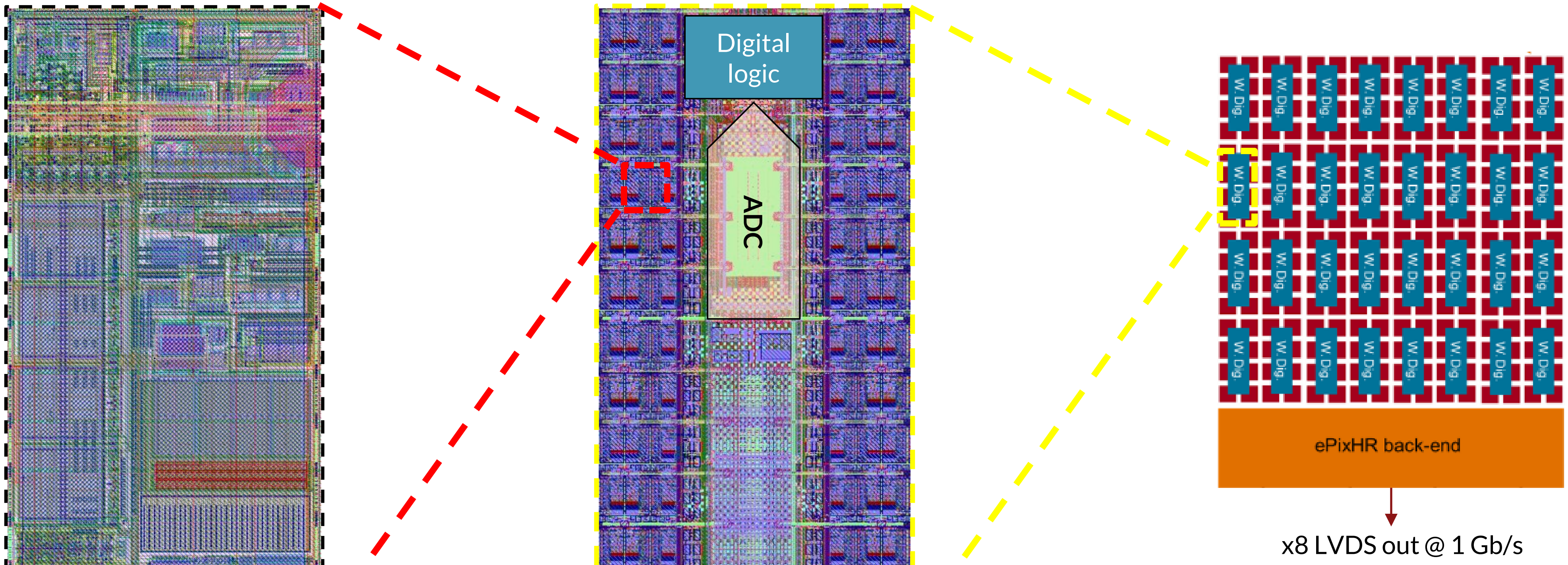


## High-resolution read-out

- The ring-buffers in each pixel are read-out
- Read-out rate: 1 MHz / (*N * 9)*
- Read-out rate in 1st prototype: 25 kHz (*N*=4)
- Can be run in "CW imager" mode: 100 kHz



# SparkPix-ED: overall architecture




## Pixel

- Operates at 35 kHz -100 kHz
- Si sensor: 100x100 μm$^2$
- ASIC: 50x100 μm$^2$

## Cluster

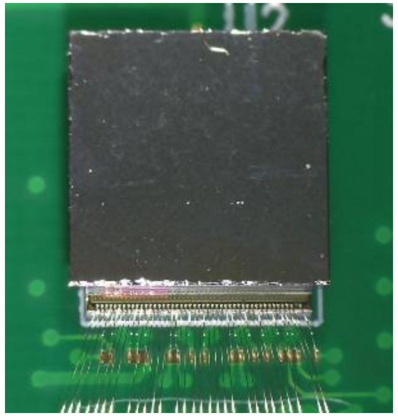
- 72 pixels → 1 ADC @ 8 MSPS, 12b
- Digital logic for pixel configuration and readout

## ASIC: 5x6 mm

Balcony includes:

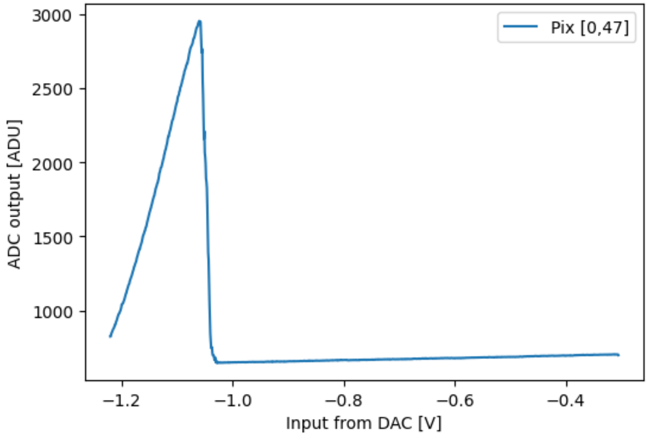
- Analog biasing
- Digital read-out logic
- Slow control/configuration

# SparkPix-ED: overview of results from 1st prototype

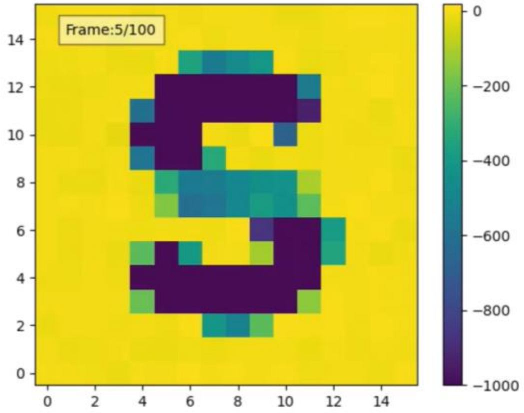


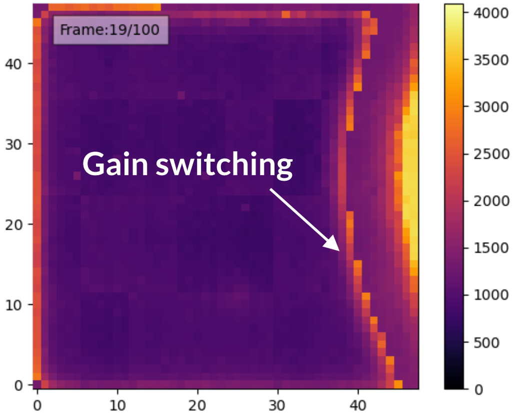
SparkPix-ED ASIC with 48x48 prototype Si sensor

Pixel response with charge injection



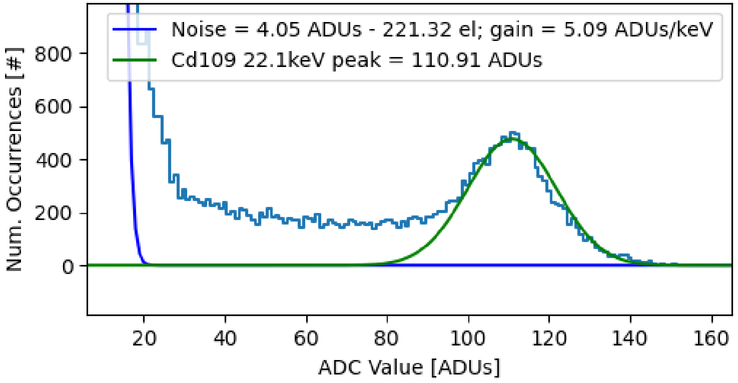

Sum: 1 MHz



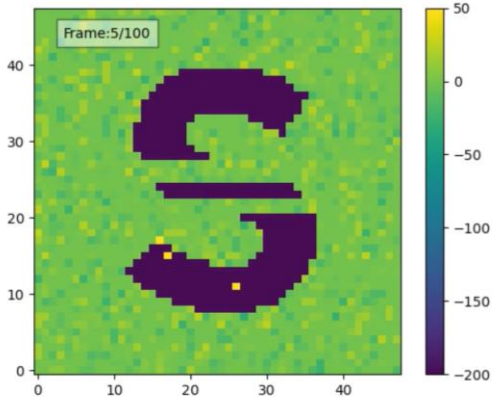




Illuminated with red laser from right side

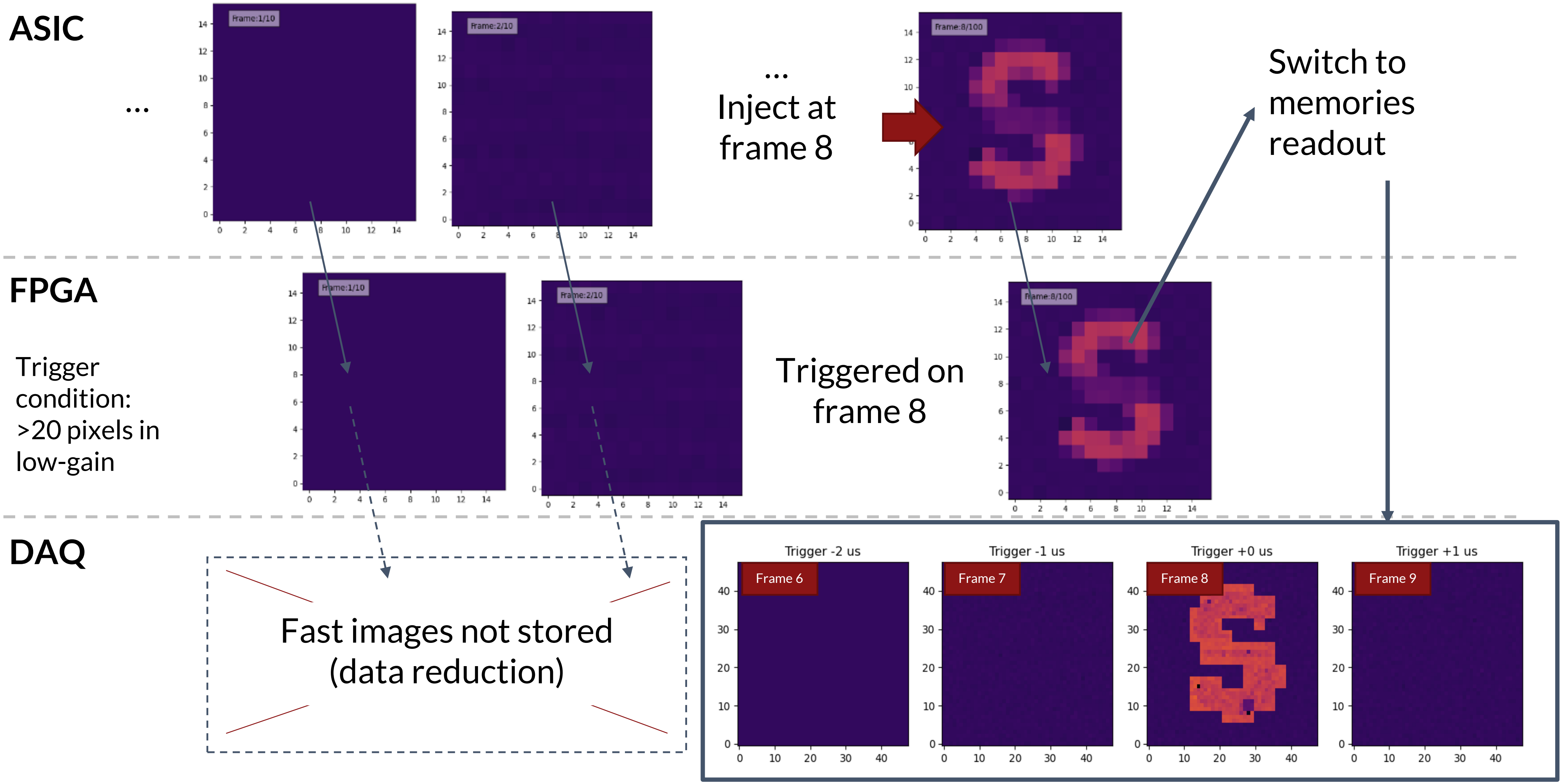
Spectrum of Cd109 source (not calibrated, raw data).




Hi-res: 0.1 MHz



# SparkPix-ED: fast trigger mode



# Energy + data compression

# SparkPix-RT

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PIs: Angelo Dragone (SLAC), Antonino Miceli (ANL), Jana Thayer (SLAC)

# SparkPix-RT: motivation

**Next-gen photon science sources are facing a data deluge problem**

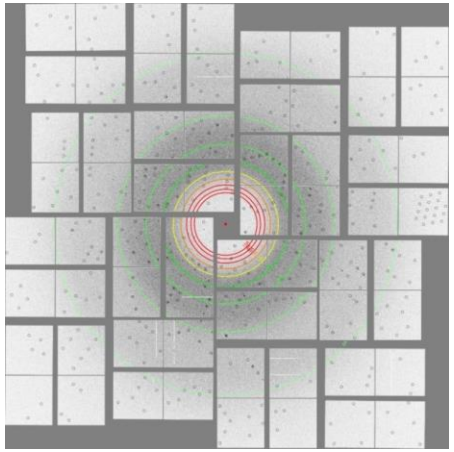
**LCLS–II:** MHz readout with on-line data reduction
**APS-U:** Increases in brightness motivate the development of high-speed scanning microscopy instruments with rates approaching 1 MHz

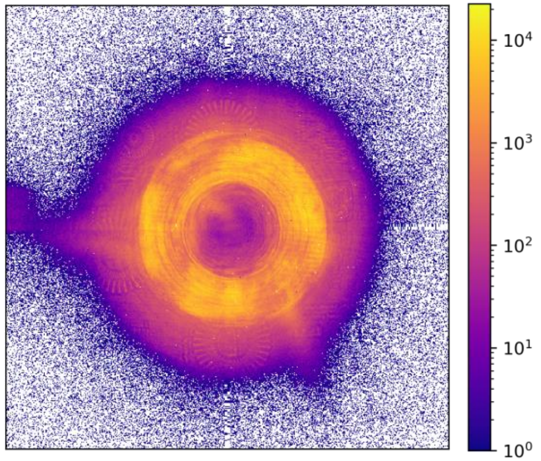
**Collaboration between Argonne & SLAC detector groups:**

- SLAC is developing ePixUHR & SparkPix family: front-end, FPGA, etc…
- ANL studying techniques for data compression on-ASIC

**Technical scope of SparkPix-RT project:**

- Evaluate real-time compression in algorithms, in-ASIC
- Leverages modularity: front-end circuitry of ePixUHR/SparkPix-ED

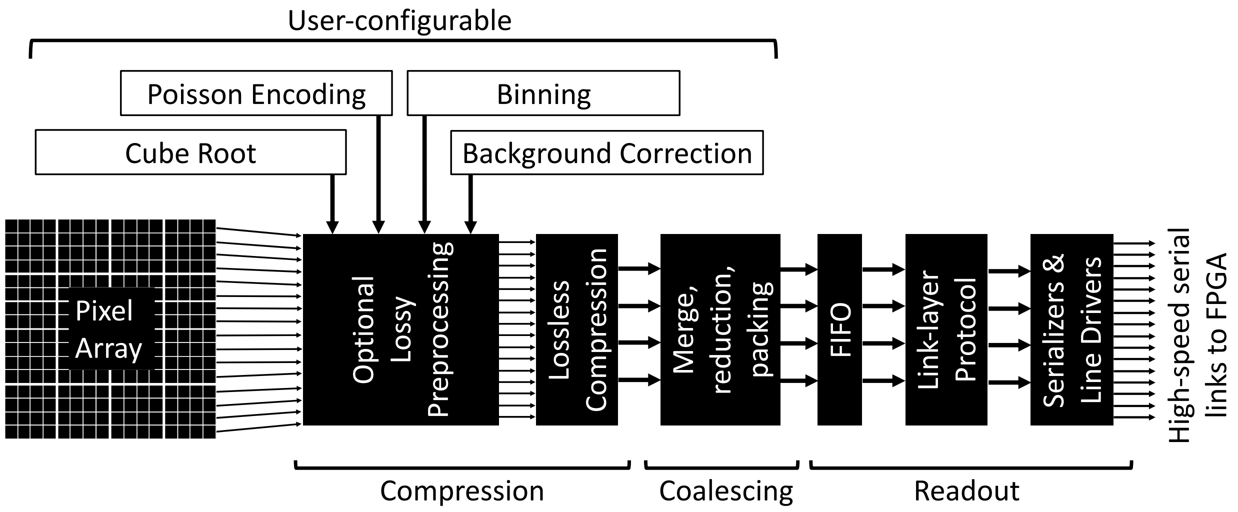




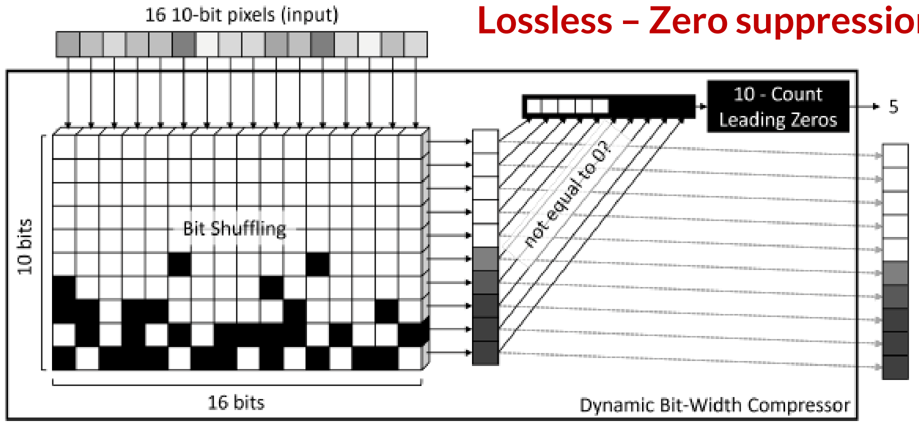

**Examples of techniques that will benefit form MHz rate detector.**
**Top: diffraction pattern at LCLS**
**Bottom: ptychography image at APS**

# Compression algorithms

## Initial Work – Compression performance on photon counting detector data




**Lossless – Zero suppression**




**Pre-processing of data depends on the type of detector**

- Photon counting: information is already quantized at pixel level
- Charge integrating: pre-processing is needed before compression → pedestal correction, thresholding, gain correction

**We are exploring techniques for on-ASIC, real-time data calibration**

# Compression algorithms

## Initial Work – Compression performance on photon counting detector data

| Dataset Name | dynamic bitwidth (Lossless) | + Poisson (Lossy) | PNG | JP2 lossless | JP2 lossy q=90 |
|---|---|---|---|---|---|
| CNM APS HXN #1 [21] | 9.98 | 13.62 | 8.45 | 12.98 | 20.31 |
| CNM APS HXN #2 [21] | 3.27 | 5.66 | 2.56 | 3.42 | 6.68 |
| MAX IV NanoMAX [22] | 5.26 | 7.74 | 4.16 | 5.18 | 19.22 |
| NSLS-II HXN [23] | 6.08 | 9.89 | 5.03 | 7.00 | 18.92 |
| APS Velociprobe [24] | 21.16 | 24.02 | 31.66 | 54.55 | 792.35 |

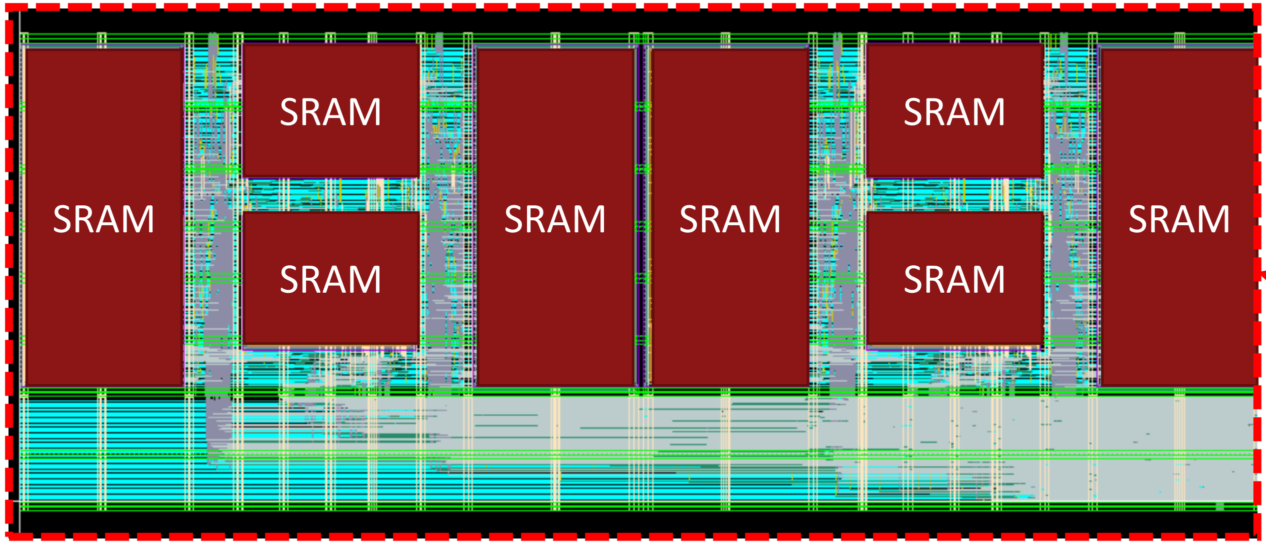
**Table 1**: Table of compression ratios with a selection of preprocessing methods and datasets.

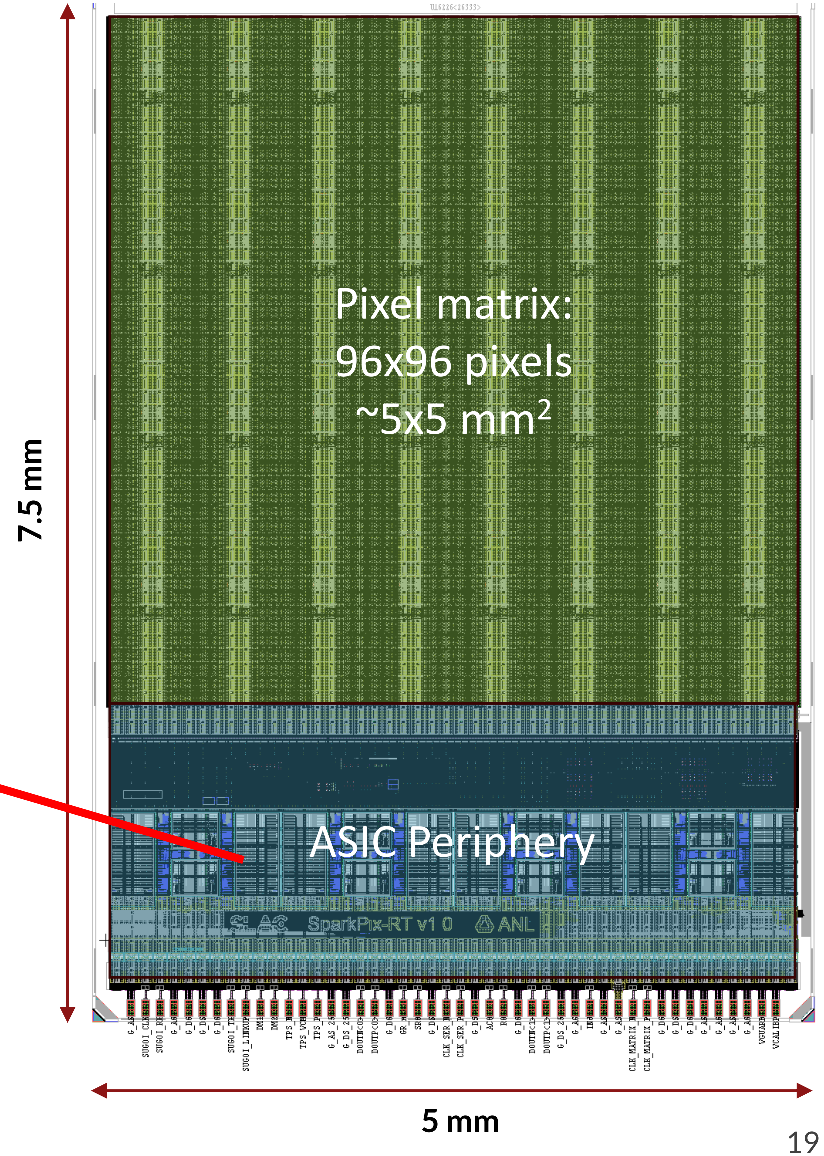
- On photon counting detector data: lossless compression performs like more complicated compression methods such as PNG and JP2
- **Co-design is key:**
  - Performance of compression algorithms is evaluated on existing data from APS & LCLS
  - … but also needs to adapt to the new ASIC front-end architecture

# SparkPix-RT: status and next steps

- Digital logic implemented in periphery of ASIC
- 1st prototype (MPW) is now in-fab, expected delivery in Aug 2023
- Working towards a 100kHz, full-scale (~2x2 $cm^2$) demonstrator

**Layout of (half) compressor digital logic**



# Energy + sparse readout

**SparkPix-S**

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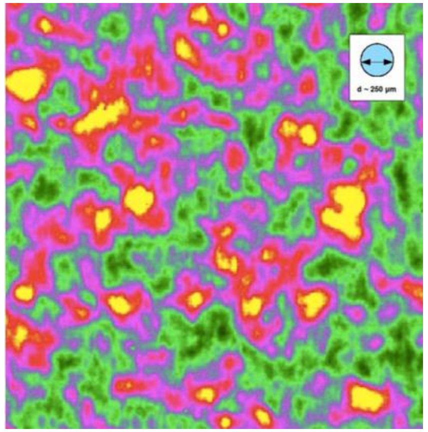
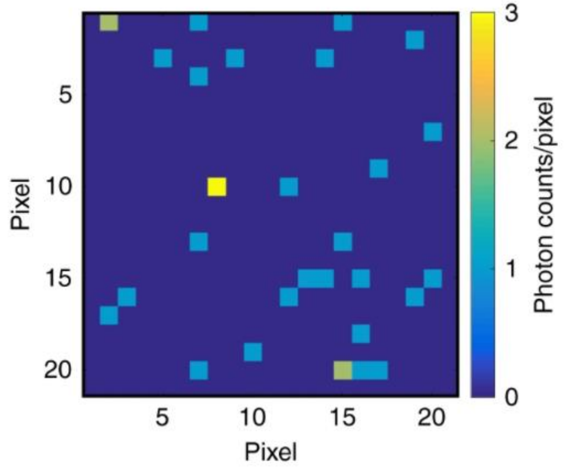
# SparkPix-S: science driver and detector needs

- X-ray Photon Correlation Spectroscopy (XPCS) and Speckle Visibility Spectroscopy (XSVS) will open new areas of science at LCLS-II:
  - Study spontaneous fluctuations at the atomic scale from microseconds down to the femtosecond timescale
  - Access stochastic fluctuations of matter on ultrafast timescales
- XPCS and XSVS experiments will benefit from a 2D integrating detector with:
  - Fine spatial resolution
  - Operating at 1 MHz, the max rate of LCLS-II
  - Discriminating between 0, 1, 2, 3…. photons/pixel/frame
  - On-line data reduction through sparsified readout



**XPCS speckle pattern**




**Signal of photon events in a small region in a speckle pattern [1]**

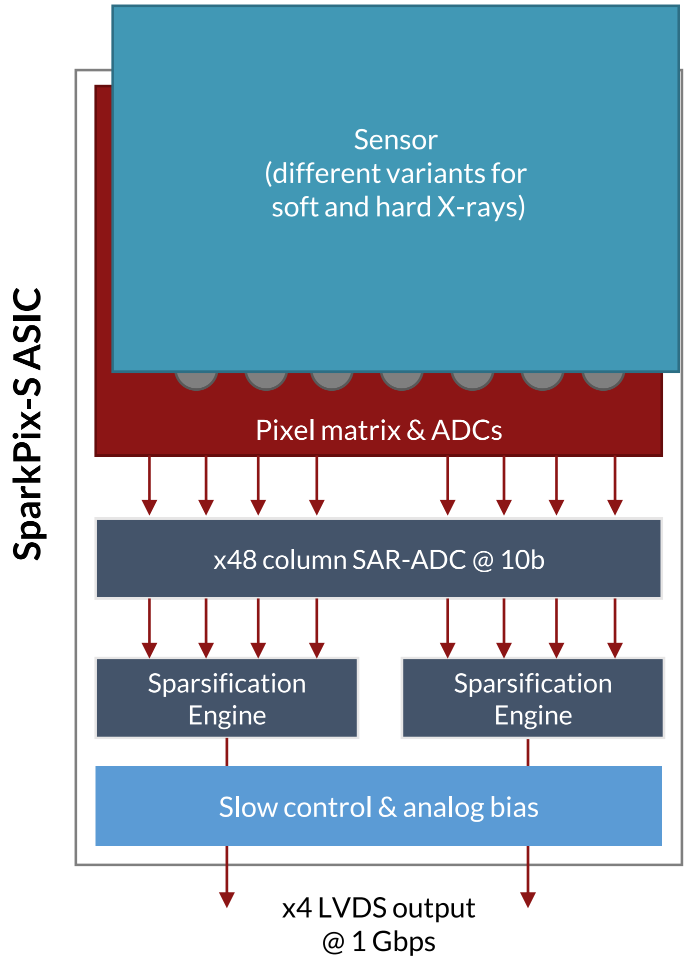
[1] W. Roseker *et al.*, Towards ultrafast dynamics with split-pulse X-ray Photon Correlation Spectroscopy at Free Electron Laser sources

# SparkPix-S: overview

- Goal is to meet the main requirements of XPCS/XSVS experiments in a single camera solution:
  - High-spatial resolution: 50um pixel pitch
  - High frame-rate: 1 MHz
  - Low-noise performance: <60 $e^-$ E.N.C.
  - Final camera size: 0.5 – 2 Mpix

- Designed to be **compatible with different sensors:**
  - 4 - 12 keV → Si sensor
  - 0.25 - 2 keV → future phase of the project (LGADs, MAPS)

- Moved away from "cluster" approach due to several reasons:
  - sparse readout, small pixel pitch (area, IR drop, routing)
- Column-parallel ADCs in periphery (adapted from ePixUHR)
- Sparsification digital engine from SparkPix-T (adapted)




**Block diagram of SparkPix-S prototype (small scale)**

# SparkPix-S: pixel overview

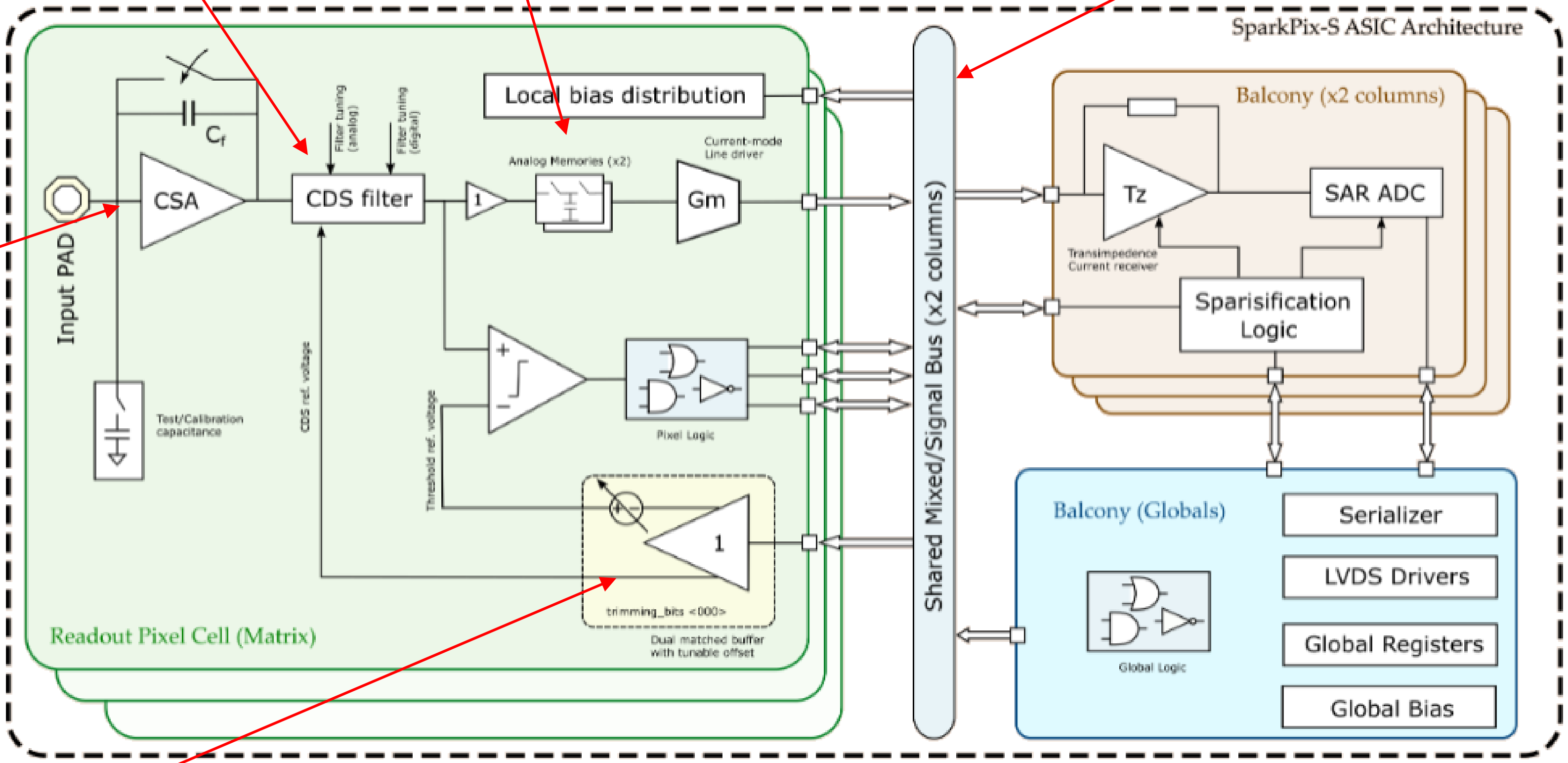
See F. Mele poster

Filter is programmable: trade frame-rate for better noise performance.

Integration and readout are pipelined using 2 analog memories.

Each pixel negotiates access to a bus shared every two columns.

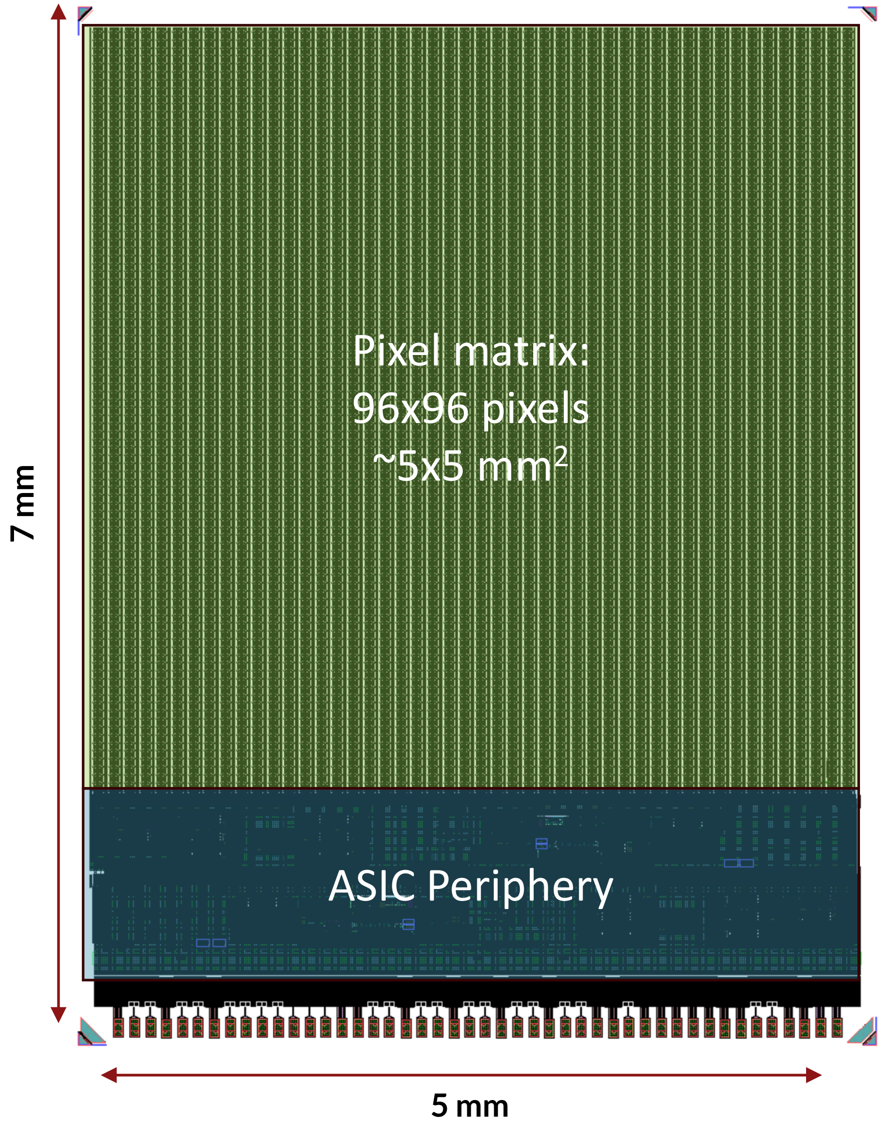
Fixed gain, dual supply, synchronous reset CSA.




Threshold generation strategy based on a matched buffers with tunable offset + auto-zeroed comparator.

# SparkPix-S: status and next steps

- **Simulated performance of first prototype:**
  - Noise: 50-55 $e^-$
  - Dynamic range: 50keV
  - Power consumption: 18 μW/pixel @ 50 μm pitch
- **Status:**
  - First MPW has been designed between July 2022 – May 2023
  - Chip delivery in August 2023
- **Towards full-scale design:**
  - 40 Gb/s output throughput needed to meet the 1% occupancy spec @ 1 MHz
  - Design of on-ASIC transceivers is being finalized
  - Prototype camera development has started
- Tape-out of first full-scale ASIC planned for mid 2024



# Photon Science: Timing + sparse readout

**SparkPix-T**

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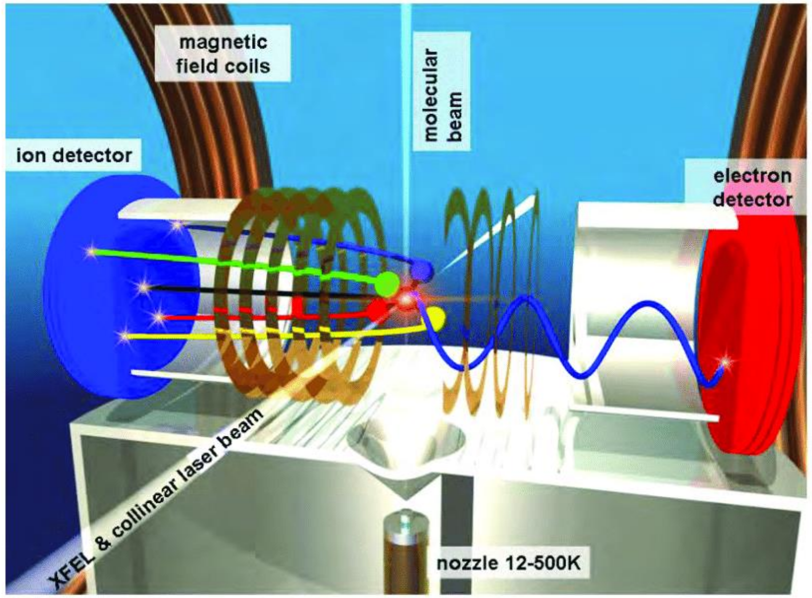
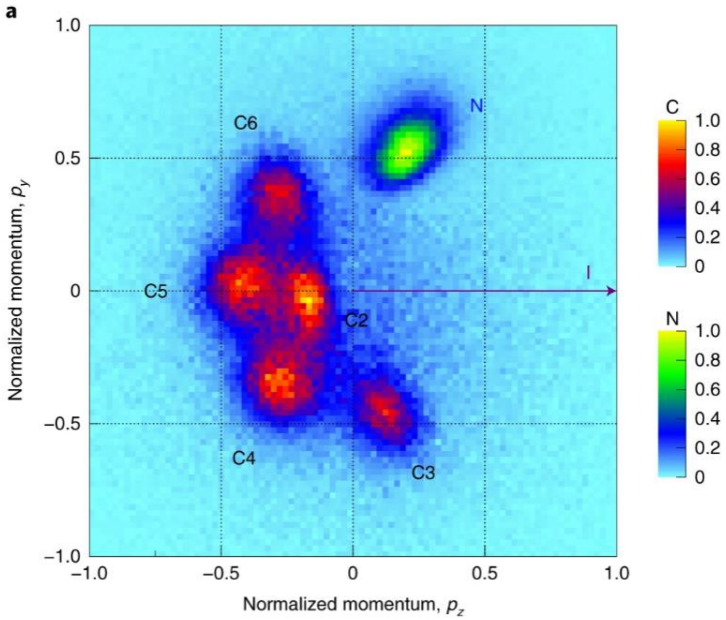
# DREAM reaction microscope at TMO




- Measure 3D momentum of ions & low-energy e$^-$: access nuclear structure
- Time resolution requirement: **250 ps**

- Currently done with MCP delay-line detectors, but:
  - 10s - 100s electrons/shot: ok for 120 Hz, problematic at high **rep-rate**
  - **MCP degradation** in hours above ~$10^6$ counts/s
  - Challenging to identify individual electron peaks without additional dimension: **degradation in resolution**
  - Delay line detector records time-of-arrival and position on detector of ionic fragments in coincidence
  - Delay line detector unable to **disambiguate** >~8 ionic fragments, as required for studies of complex systems



Boll *et al.*, Nature Physics, 2022

# SparkPix-T: timeline and requirements

- **Tixel** - origin: LDRD - prototype ASIC fabricated and tested, demonstrated timing **2014-2016**
- **SparkPix-T** v0.1 prototype (48x48 pixels), additional features added **2019-2021**
- **SparkPix-T** v0.2 prototype (48x48 pixels), fixed bugs **2021-2022**
- **SparkPix-T** v1.0: full-size ASIC fabricated, testing in progress **2022-2023**

| | SparkPix-T Specifications |
|---|---|
| Mode of Operation | Time of Arrival (+ ToT) |
| Timing resolution | 100ps |
| Time depth | 6.5μs (16bit) |
| TOT | 8bit |
| Technology | 0.13μm |
| Pixel size | 100x100 $\mu m^2$ |
| Array | 176x192 (48x48 prototype) |
| Frame rate (Occupancy) | 5kHz (100%), 100kHz (5%), 1MHz (0.5%) |
| Range | 10keV-100keV (0.44fC- 4.4fC) |
| Max Hit rate / area | 49Mhit/s/$cm^2$ |
| Gating | min 20ns |

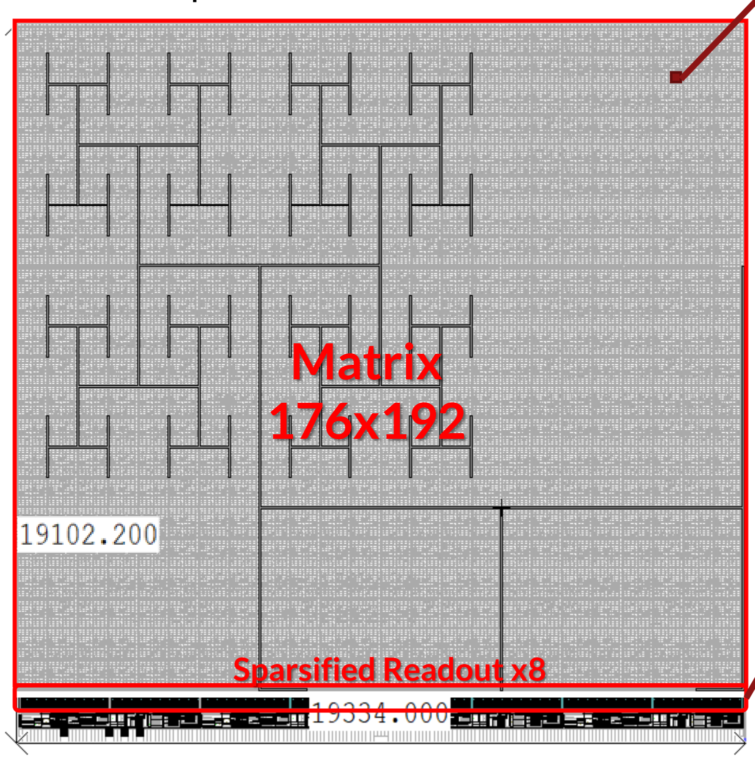
**Additional features requested:**

- **Gating of the preamp** in pixel to reject "background" photons
  - LCLS pulse creates "background" photons at t=0 (florescence due to LCLS pulse, scattered X-ray photons, stray light in the range of 0.3-2 keV)
  - Deadtime caused by "background" photons can lead to signal loss in the time interval of interest
- **Sparsified readout:** two ways to handle over-occupancy:
  - Flush data → typical, data over-occupancy are lost
  - Paralyze system → prevent new acquisitions until all the data are readout
  - If specs are exceeded, users notified **in real-time**

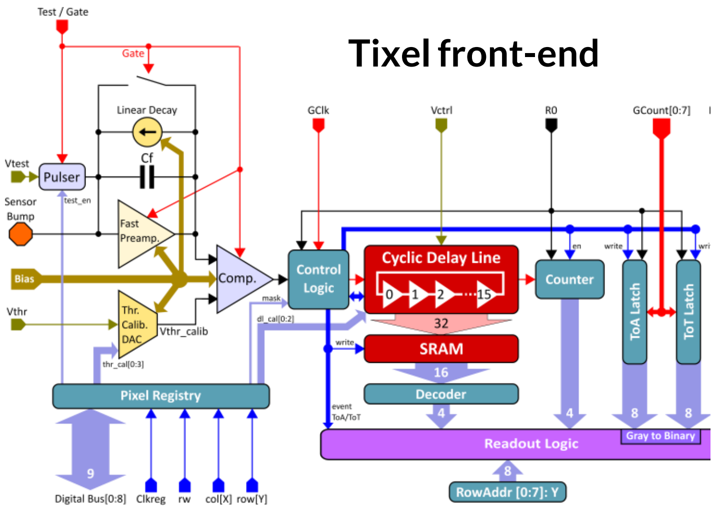
# SparkPix-T: architecture

Prototype SparkPix-T:


Full-size SparkPix-T:




## Pixel (100x100um²)

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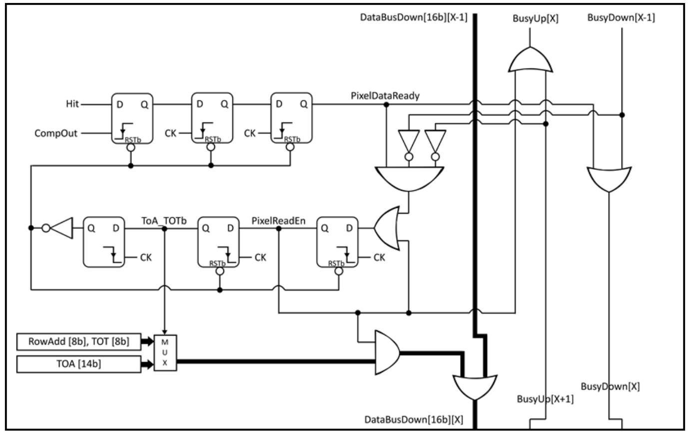
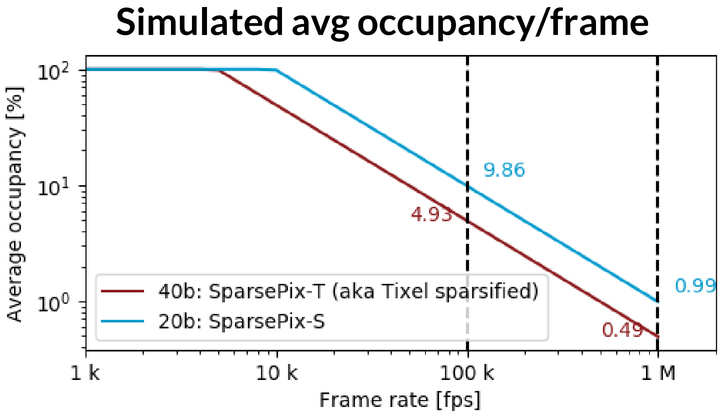
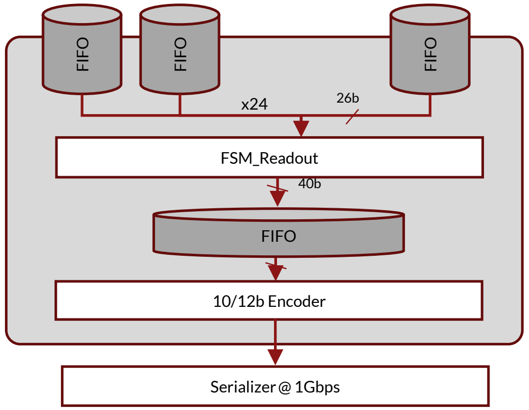



Sparsified Readout per Column

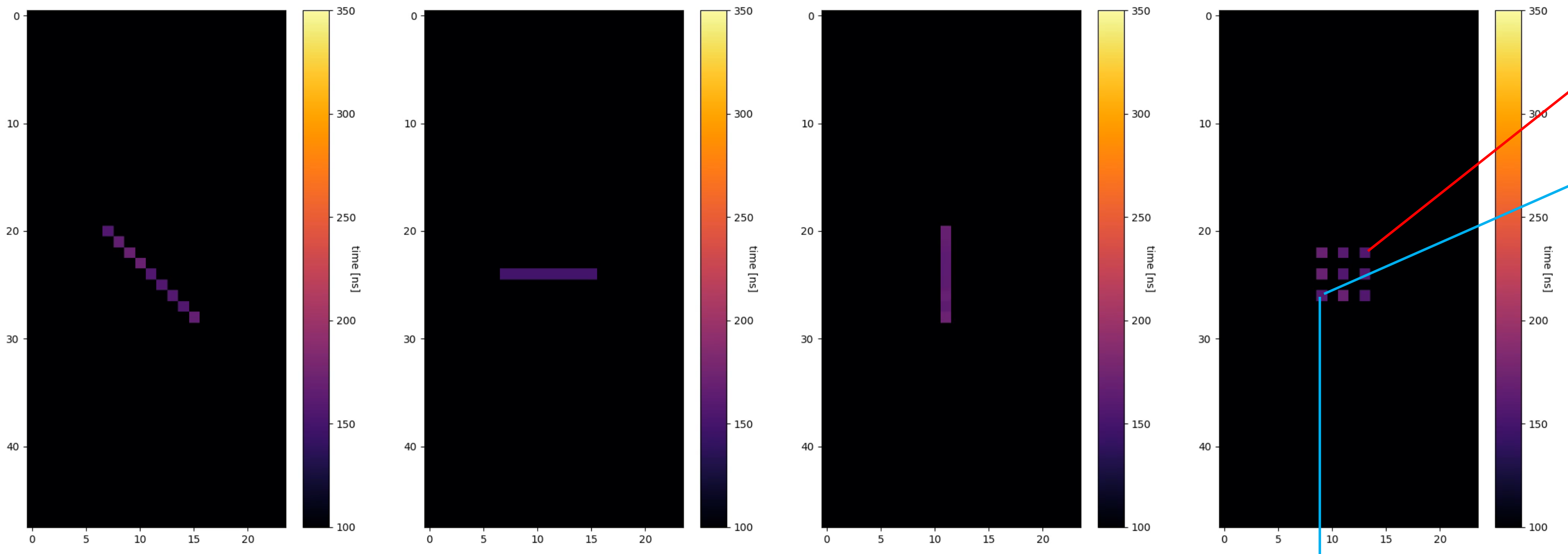
## Sparse digital readout (every 24 columns): can be tailored to different ASICs

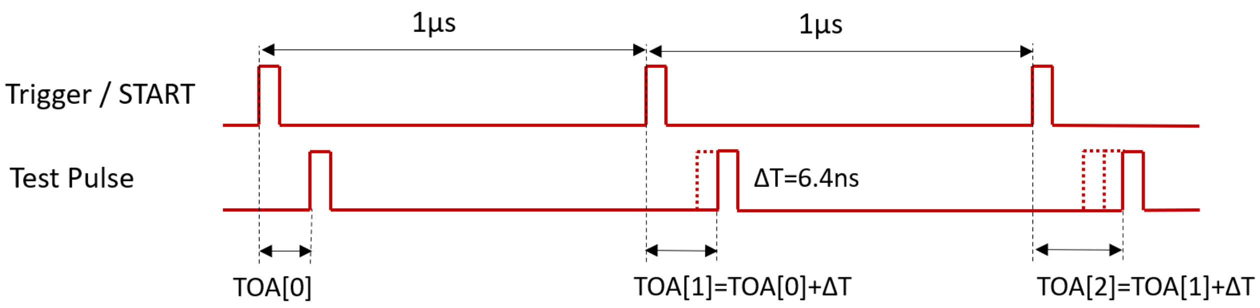


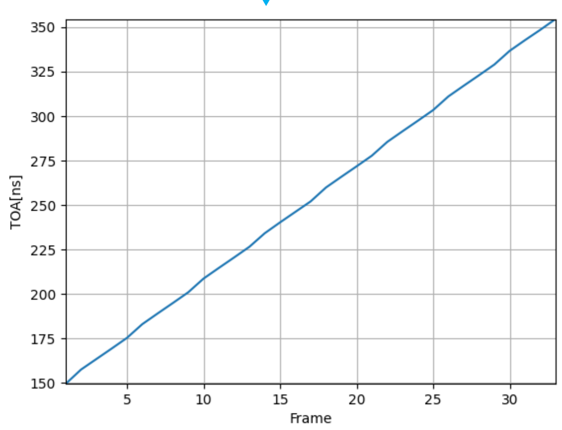



# SparkPix-T: sparsified readout

- Readout at **1MHz** frame rate:




- Sparsified data stream:

```
trig=0  col=11  row=22  TOT=15  ToA_C=7  ToA_F=97
trig=0  col=13  row=22  TOT=15  ToA_C=7  ToA_F=97
trig=0  col=9   row=24  TOT=15  ToA_C=7  ToA_F=97
trig=0  col=11  row=24  TOT=15  ToA_C=7  ToA_F=98
trig=0  col=13  row=24  TOT=15  ToA_C=7  ToA_F=96
trig=0  col=13  row=26  TOT=15  ToA_C=7  ToA_F=99
trig=0  col=9   row=26  TOT=15  ToA_C=7  ToA_F=99
trig=0  col=11  row=26  TOT=15  ToA_C=7  ToA_F=99
trig=1  col=13  row=22  TOT=15  ToA_C=7  ToA_F=157
trig=1  col=9   row=22  TOT=15  ToA_C=7  ToA_F=158
trig=1  col=11  row=22  TOT=15  ToA_C=7  ToA_F=156
trig=1  col=11  row=24  TOT=15  ToA_C=7  ToA_F=157
trig=1  col=13  row=24  TOT=15  ToA_C=7  ToA_F=156
trig=1  col=9   row=24  TOT=15  ToA_C=7  ToA_F=156
trig=1  col=9   row=26  TOT=15  ToA_C=7  ToA_F=157
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trig=1  col=13  row=26  TOT=15  ToA_C=7  ToA_F=158
trig=2  col=9   row=22  TOT=15  ToA_C=7  ToA_F=220
trig=2  col=11  row=22  TOT=15  ToA_C=7  ToA_F=218
trig=2  col=13  row=22  TOT=15  ToA_C=7  ToA_F=218
trig=2  col=13  row=24  TOT=15  ToA_C=7  ToA_F=218
trig=2  col=9   row=24  TOT=15  ToA_C=7  ToA_F=218
trig=2  col=11  row=24  TOT=15  ToA_C=7  ToA_F=220
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trig=2  col=9   row=26  TOT=15  ToA_C=7  ToA_F=218
trig=3  col=11  row=22  TOT=16  ToA_C=8  ToA_F=36
trig=3  col=13  row=22  TOT=16  ToA_C=8  ToA_F=37
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trig=4  col=13  row=26  TOT=16  ToA_C=8  ToA_F=99
trig=4  col=9   row=26  TOT=16  ToA_C=8  ToA_F=99
trig=4  col=11  row=26  TOT=16  ToA_C=8  ToA_F=100
```

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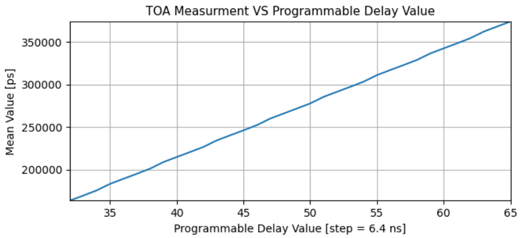
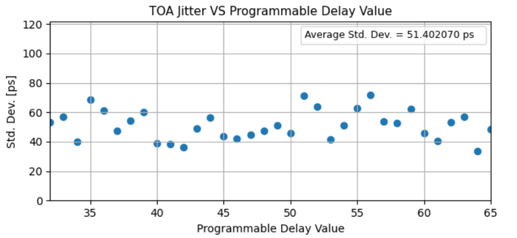
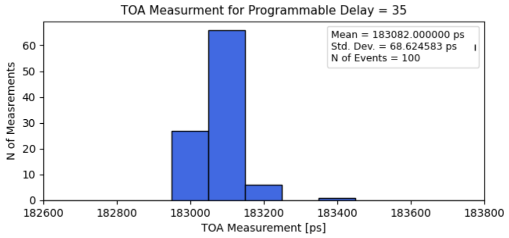
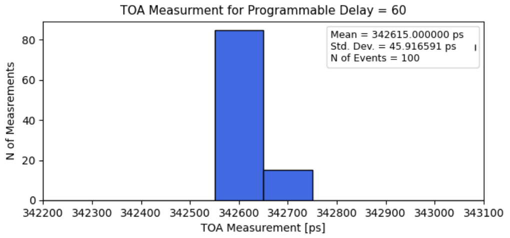
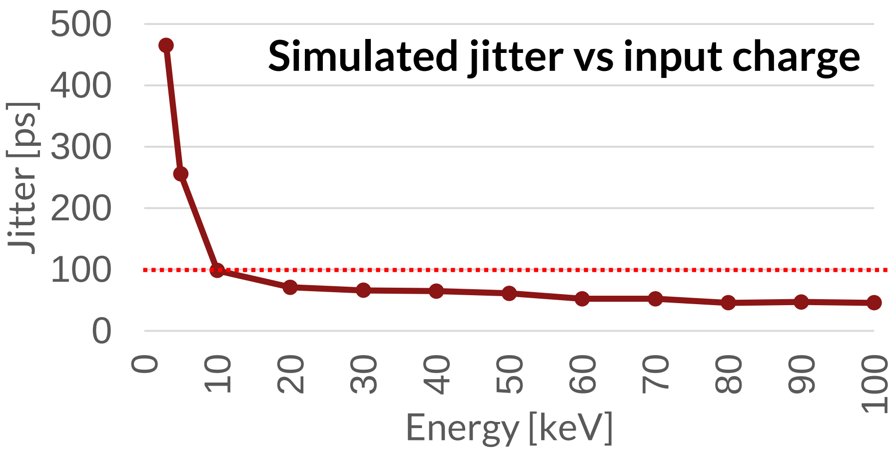
# SparkPix-T: timing performance

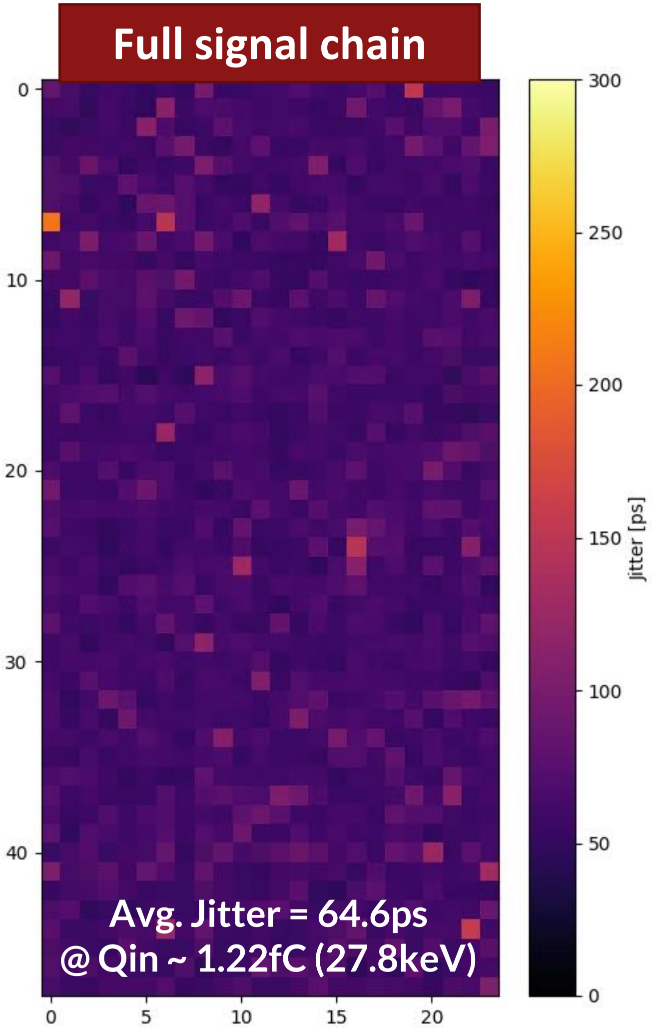


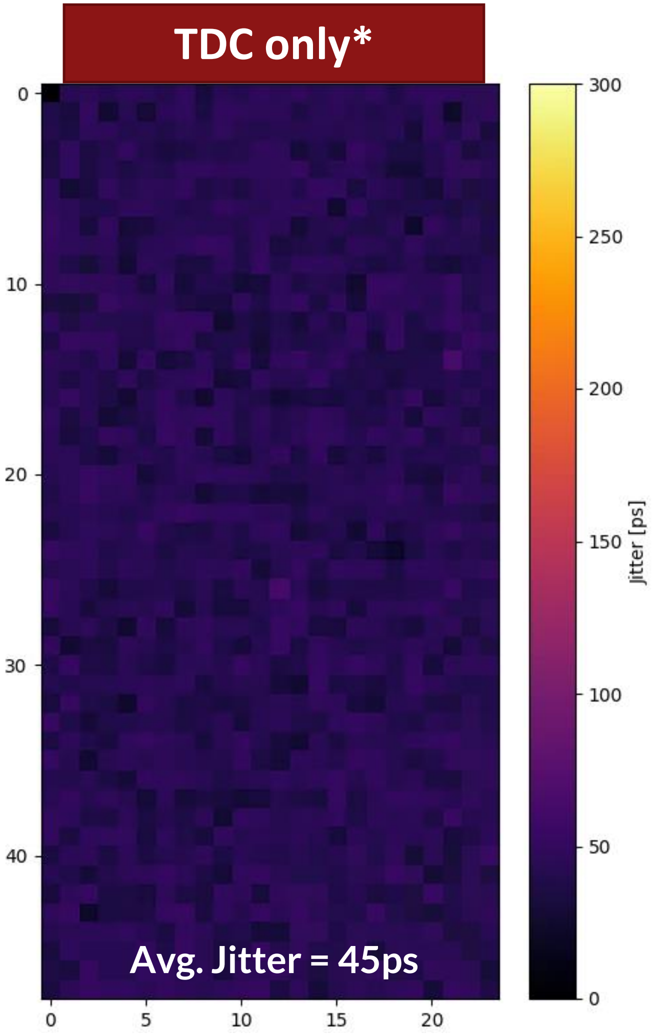




- **Measured:** jitter <100ps for Qin > 10keV

*includes jitter contributions from TDCs, reference clock jitter, test-pulse jitter, clock and test-pulse distribution trees.*

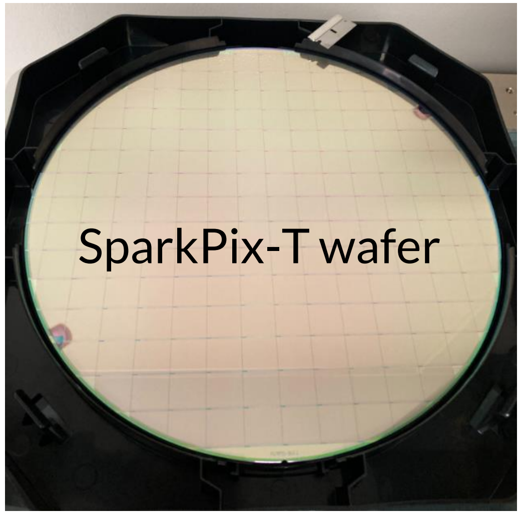
# SparkPix-T: summary & next steps

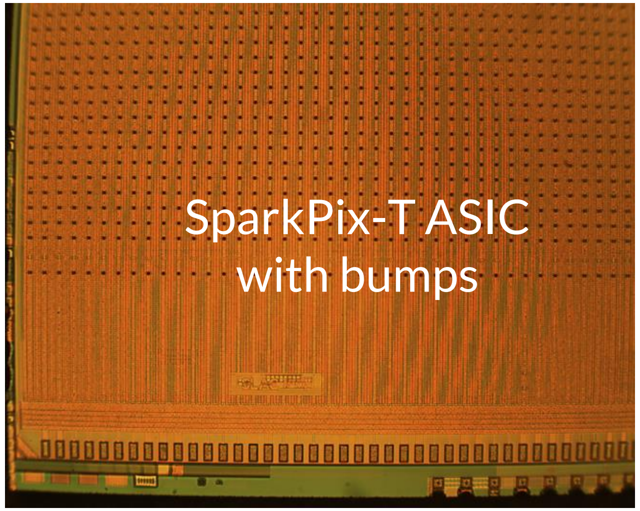
## Status:

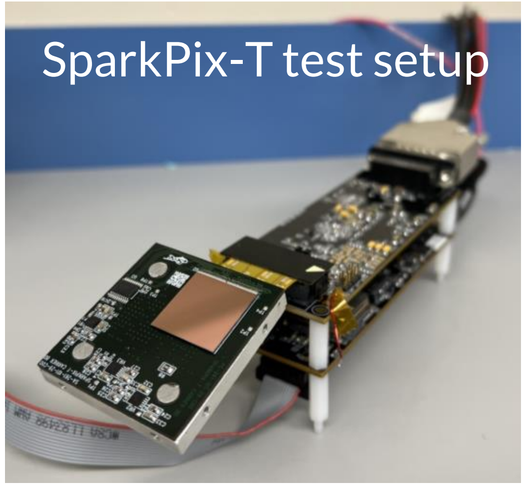
- First full-reticle ASIC on CMOS 130 nm: 176x192 pixel array with sparsification engine and 8 Gb/s output bandwidth
- Wafers received
- Readout card and FPGA firmware/software ready (C. Bakalis, D. Doering)
- Testing in progress

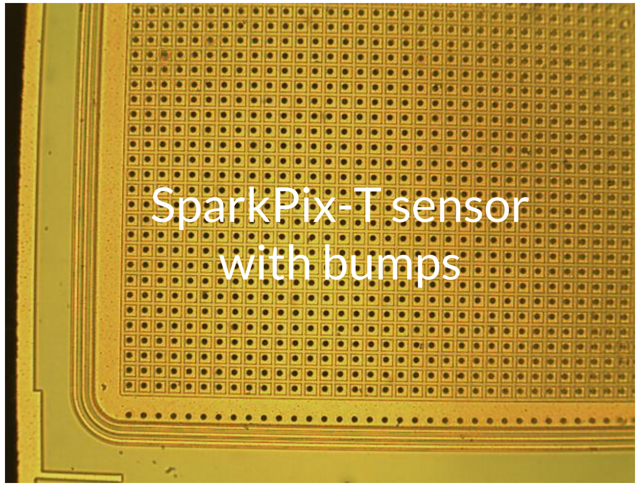
## Next steps:

- Test-bench characterization of the full-size ASIC
- Camera prototype demonstration at TMO
- Upgrade I/Os to ~5Gbps/channel
- Follow-up project with LGADs for 0.5 Mpix camera



# Summary

# Summary

**SLAC is developing a new family of ultra high-rate X-ray detectors to meet the science goals of LCLS-II / LCLS-II-HE**

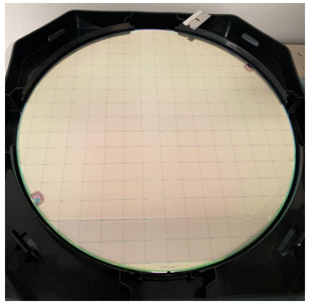
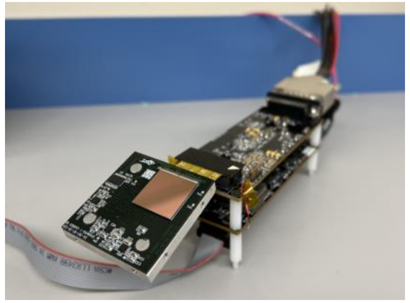
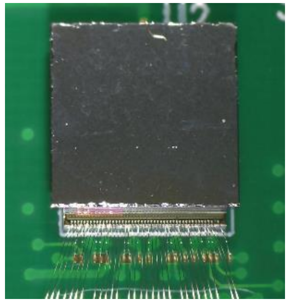
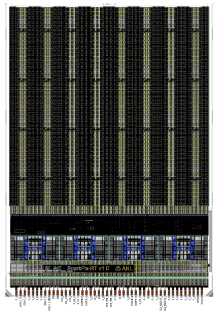
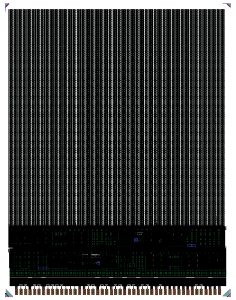
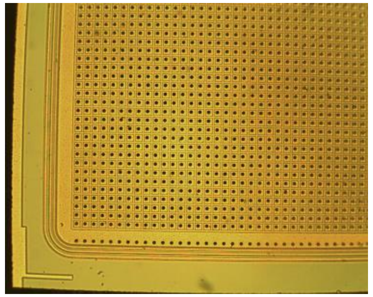
Tomorrow

### Full-frame detectors:

- **ePixUHR-35kHz:** first large-scale ASIC functional, characterization on-going
- **ePixUHR-100kHz:** upgrade clocking & increase output throughput, $1^{st}$ prototype in 2024

### Detectors with on-ASIC information extraction:

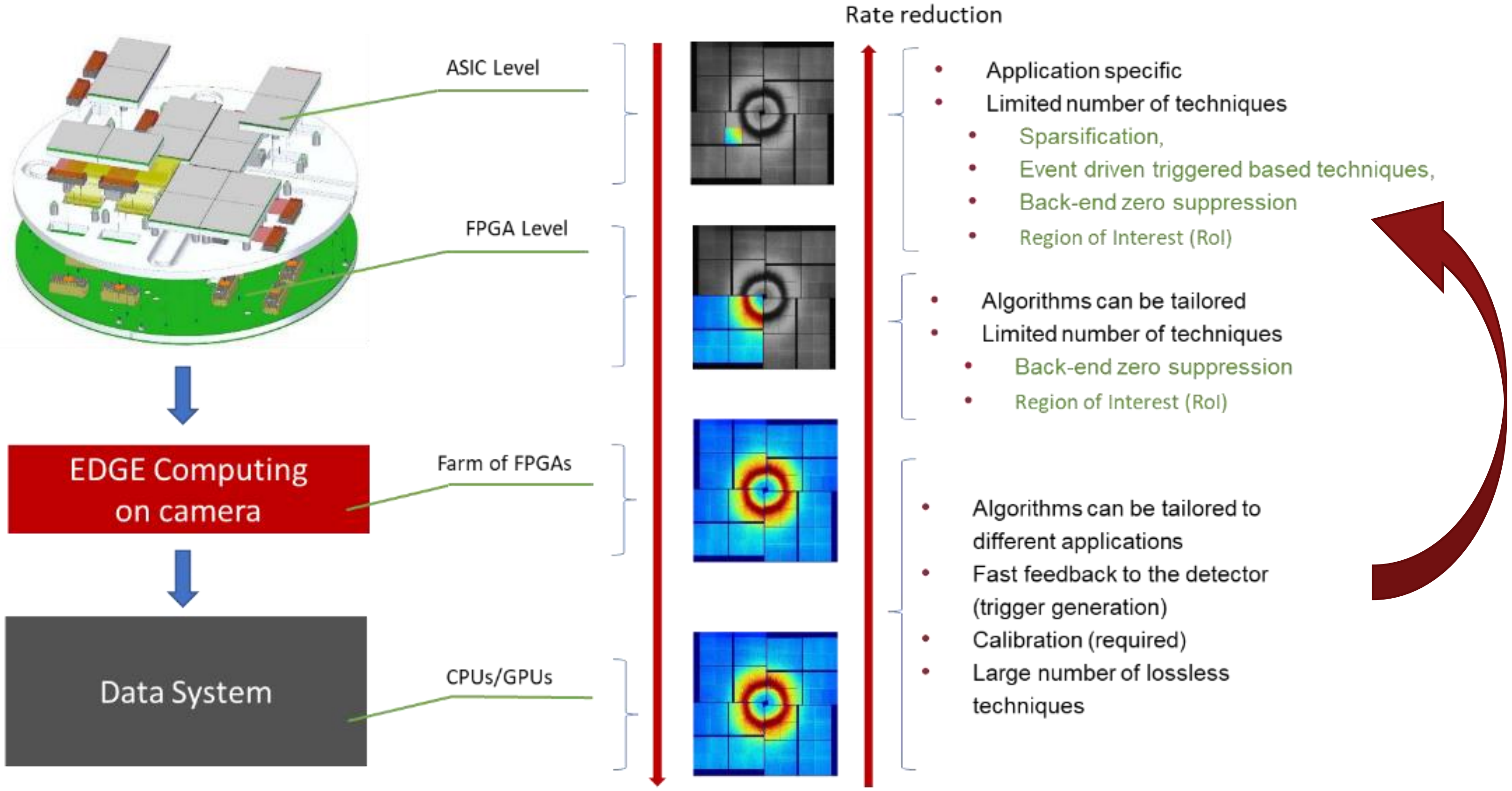
- **SparkPix-T:** $1^{st}$ full-scale prototype is alive, characterization on-going, next: beam-time at TMO beamline
- **SparkPix-ED:** $1^{st}$ prototype demonstrated low-latency feedback, re-assessing science specifications
- **SparkPix-RT:** $1^{st}$ MPW in fab, currently scaling the design to full-scale for late 2023 submission
- **SparkPix-S:** $1^{st}$ MPW in fab, characterization will start in fall, full-scale ASIC in mid-late 2024

# Future research directions

## What is the path forward?

- Distributed processing for efficiency (energy, information)
- Leverage AI/ML for real time data extraction with low latency (*e.g.*, SNL library)
- Develop adaptive data driven readout architectures
- Develop supporting technology for high-bandwidth, on-detector communication
- Adopt beyond CMOS technologies with heterogenous integration




**Push computing as close as possible to the source**

A. Dragone - see also *R. Herbst, Edge Data Processing, ULITIMA 2023*