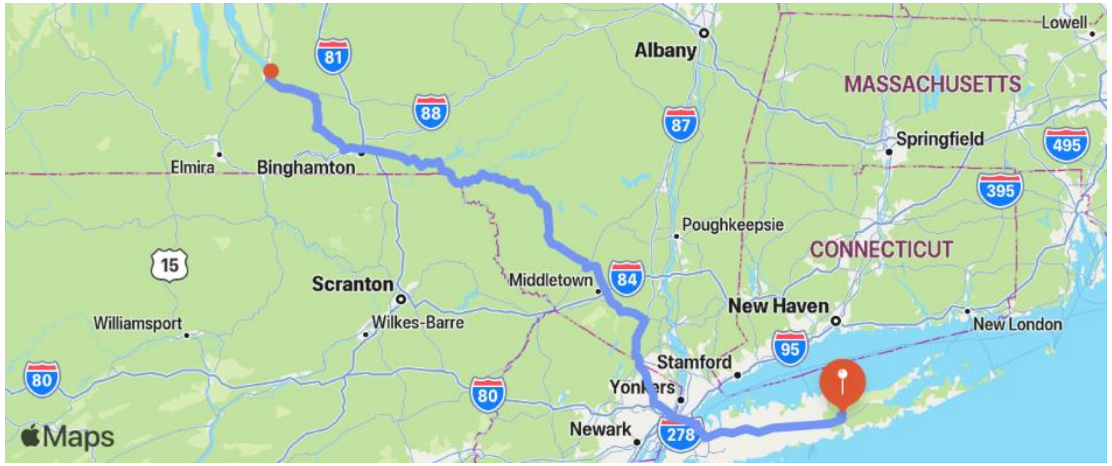
Integrating imaging detectors: from CCDs to hybrid pixel detectors

in photon science

Julia Thom-Levy

Sol Gruner



Cornell University

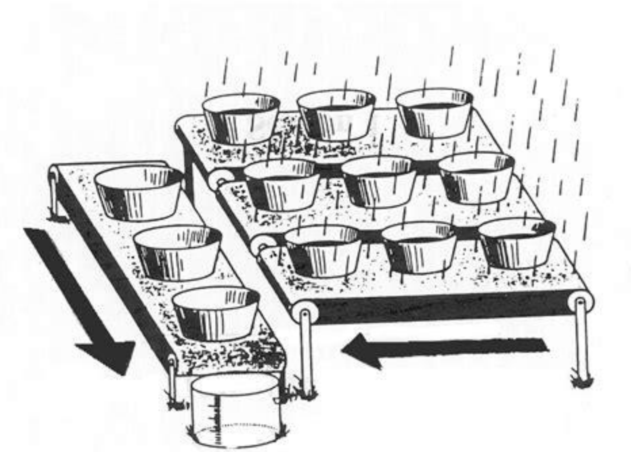
Brookhaven National Laboratory

The quest for “wide dynamic range”

Integrating imaging pixel detectors

Monolithic

- Charge-Coupled Device (CCD)
- CMOS imagers



Hybrid pixel detectors

- Sensors in high resistivity silicon or other semiconductors
  - Pixel Array Detectors (PAD), DEpleted P-channel Field Effect Transistor (DEPFET), X-ray Active Matrix Pixel Sensors (XAMPS)…
- Readout chip in low resistivity silicon - standard IC technology
- *…and combination of the above*

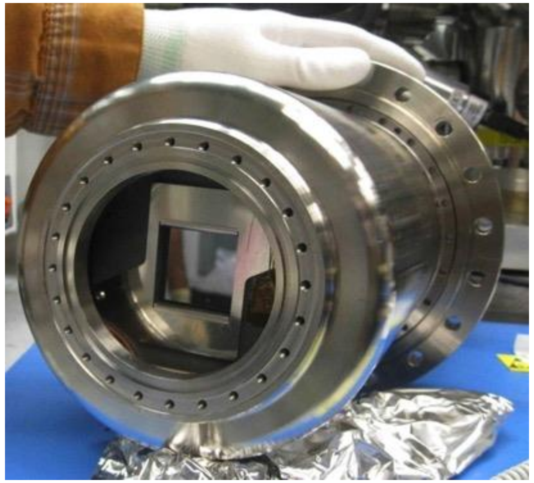
George Smith and Willard Boyle

Invention of the ‘Charge Bubble’ Devices in 1969

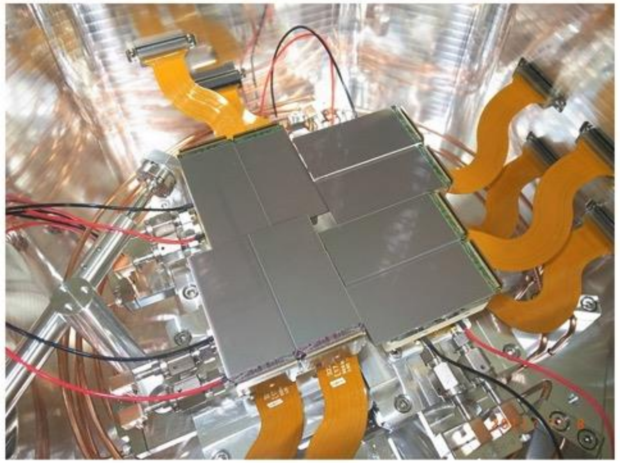
Nobel Prize for Physics in 2009

Charge-coupled devices for x-rays imaging

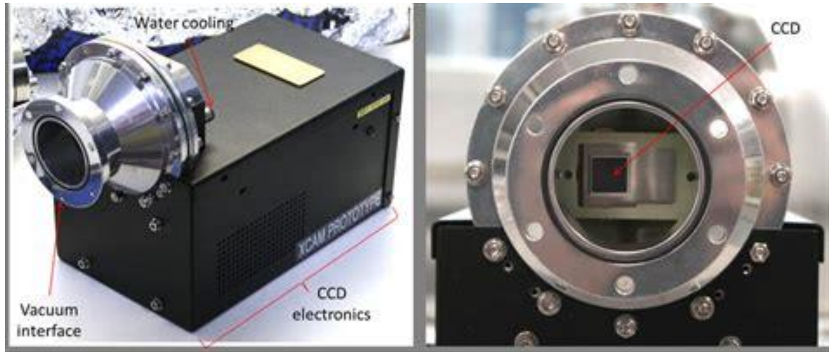
scintillator
fiber coupled
to CCD



FCCD, LBNL

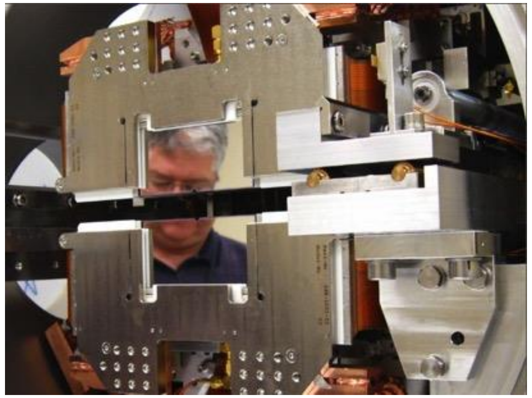


MPCCD, Riken, Japan



EM-CCD, XCAM

SOPHIA (L), PIXIS (R)
Princeton /Teledyne



pnCCD, MPG-HLL

Bump-bonded Pixel Array Detectors (PADs)

X-ray Conversion Layer

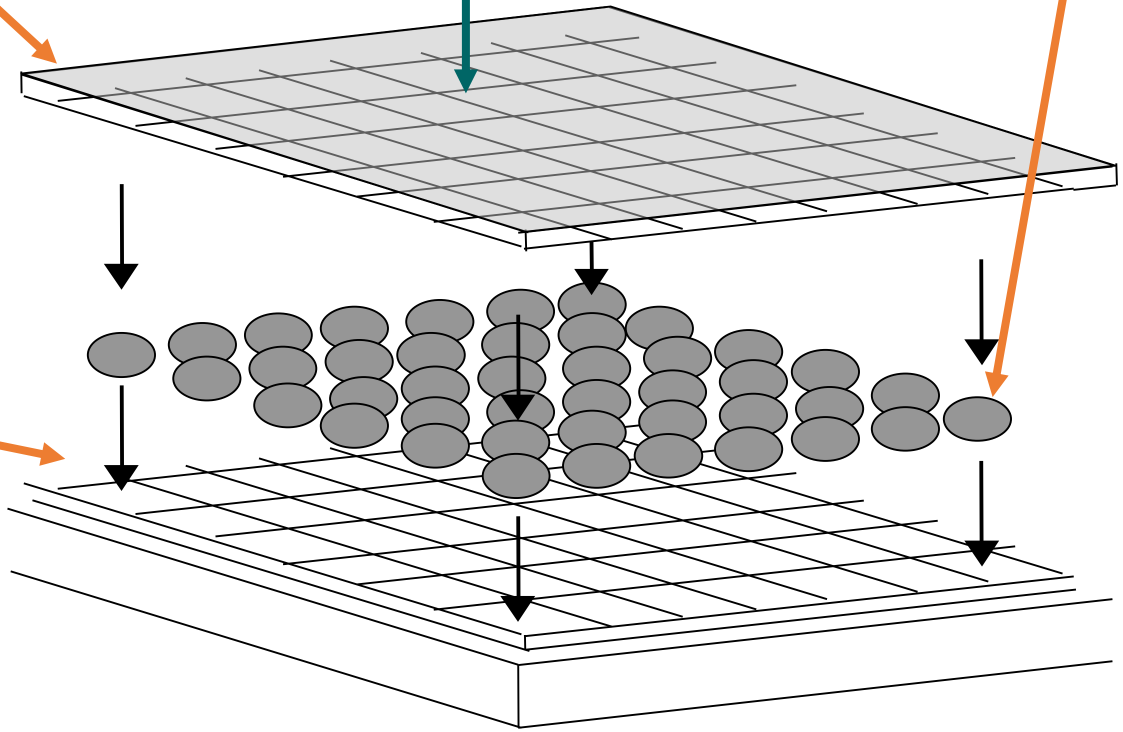
e.g., Si, CdTe: 0.5 - 1 mm thick

- Large signal/x-ray
  Single photon sensitivity
- Single pixel PSF
- Prompt signal collection

Signal Processing Layer

Application Specific Integrated Circuit (ASIC) – Si CMOS

- Each pixel has own processing electronics



X-rays

Bump Bonds

1 per pixel

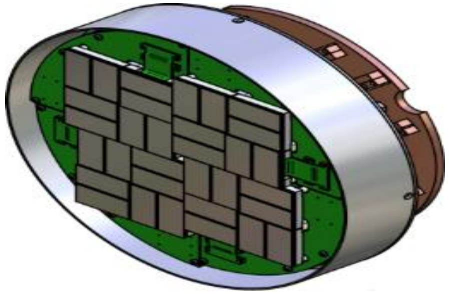
Bump-bonded PADs come in two varieties

SLS PILATUS

Photon counting PADs

- Front ends count each x-ray individually (PILATUS, Medipix, Timepix, XPAD, etc.)

Integrating PADs (our primary focus)



Cornell-SLAC LCLS

- Use an integrating front-end to avoid the count-rate bottleneck
- Only PAD option for most XFEL and many storage ring experiments
- Single photon sensitivity
- Variants include CS-PAD, MM-PAD, Keck-PAD, AGIPD, LPD, JUNGFRAU, etc.

Bump-bonded PADs come in two varieties

Photon-counting PADs

- Front end counts each x-ray individually
- Suppress pixel read noise and dark current
- Count-rate limited to ~10^6 -10^7 x-rays/pix/s (depending on source characteristics)
- Pixel well capacity (max. detectable signal per frame) set by counter depth

Photon-integrating PADs

- Front end measures the integrated energy deposited in the sensor during a frame
- Dark current must be subtracted; care required to *minimize* read noise
- Count-rate bottleneck avoided - Only option for most XFEL experiments and intense single-bunch imaging.
- Well-depth limited by pixel storage capacity to ~1000's of photons/pixel/frame
  - …but well-depth extension techniques can boost this to >10^7 x-rays/pixel/frame

Need for integrators: dynamic range

- Many problems need many photons/pix/frame
- Photon counters: hard to distinguish 2 x-rays/pix arriving in few x100ns
- In APS std. mode instantaneous intensity:

$$I_{\text{instantaneous}} = \left(\frac{\tau_{\text{bunch interval}}}{\tau_{\text{bunch duration}}} \right) I_{\text{avg}}$$

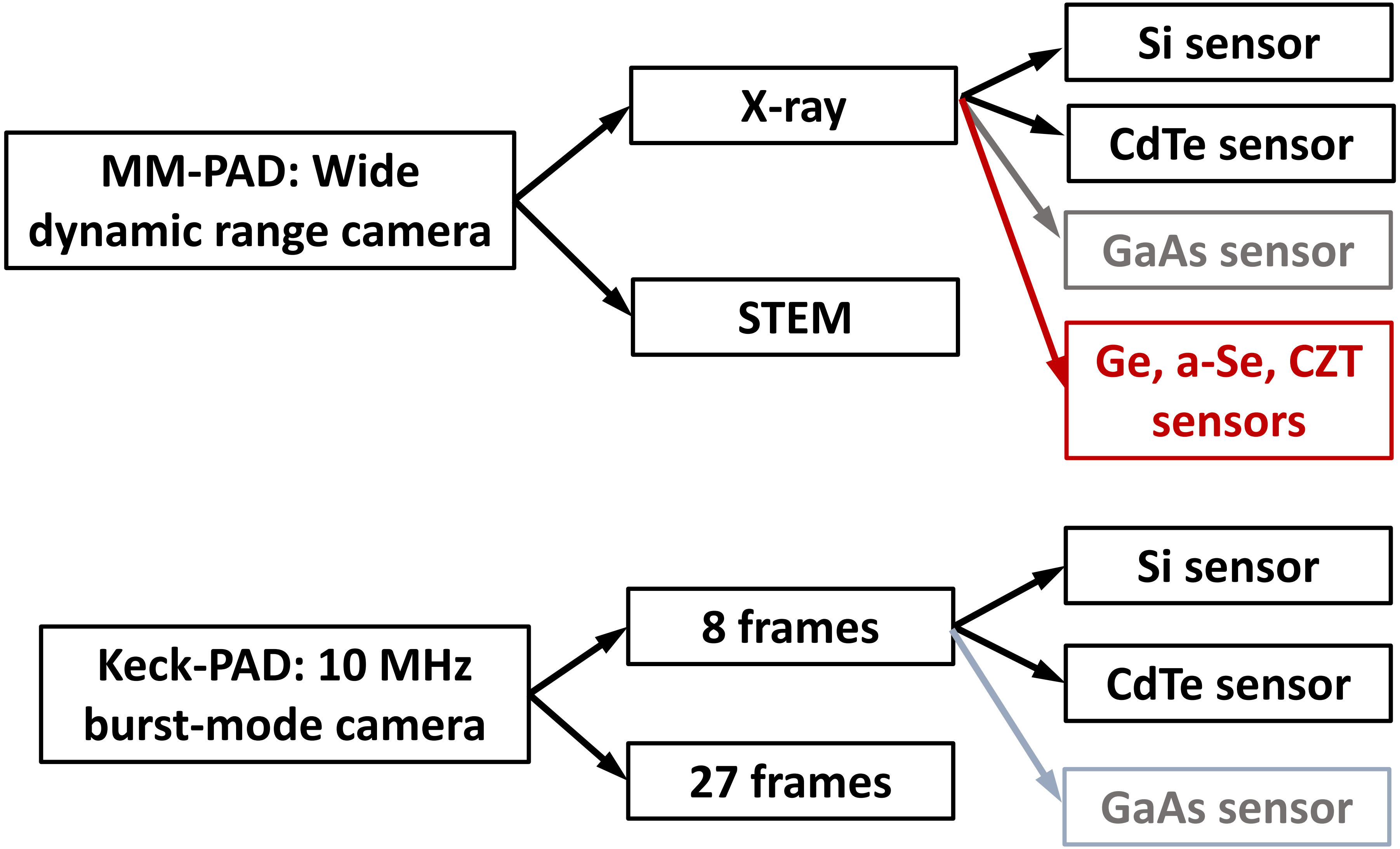
≈ 4000 x average intensity

- Stochastic arrival makes it worse

The dynamic range of a photon counter is count-rate dependent

'Fast & precise: these detectors offer single-photon counting, with a count rate up to ***10^7 ph/s/pixel****.'*

Two families of integrating detectors


MM-PAD: Wide dynamic range camera

X-ray

STEM

Si sensor

CdTe sensor

GaAs sensor

Ge, a-Se, CZT sensors

Keck-PAD: 10 MHz burst-mode camera

8 frames

27 frames

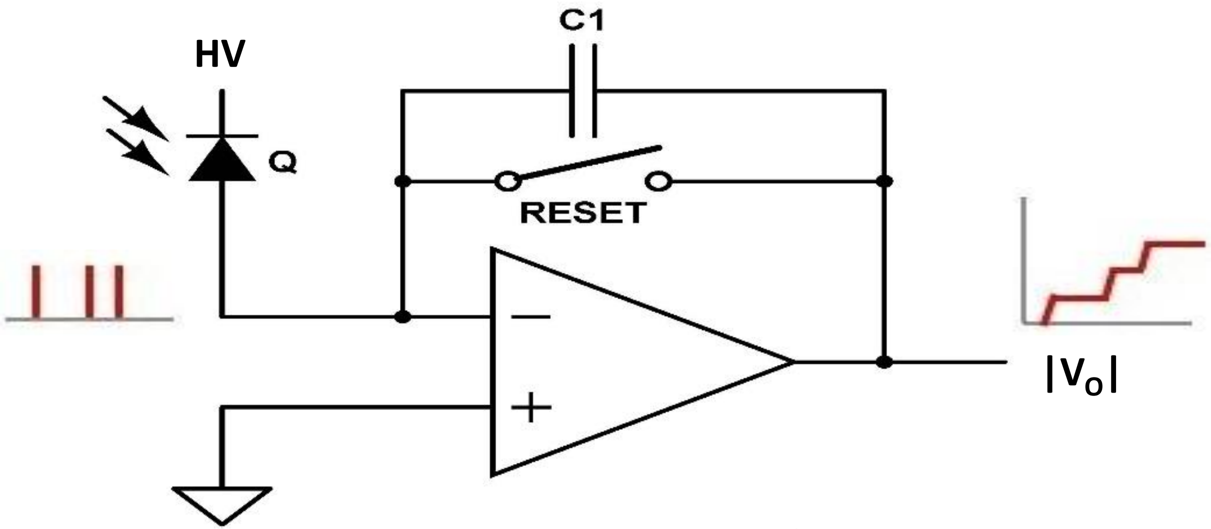
Si sensor

CdTe sensor

GaAs sensor

Both families: 150 µm x 150 µm pixel size, 256 x 384 pixel tiled systems assembled @ Cornell

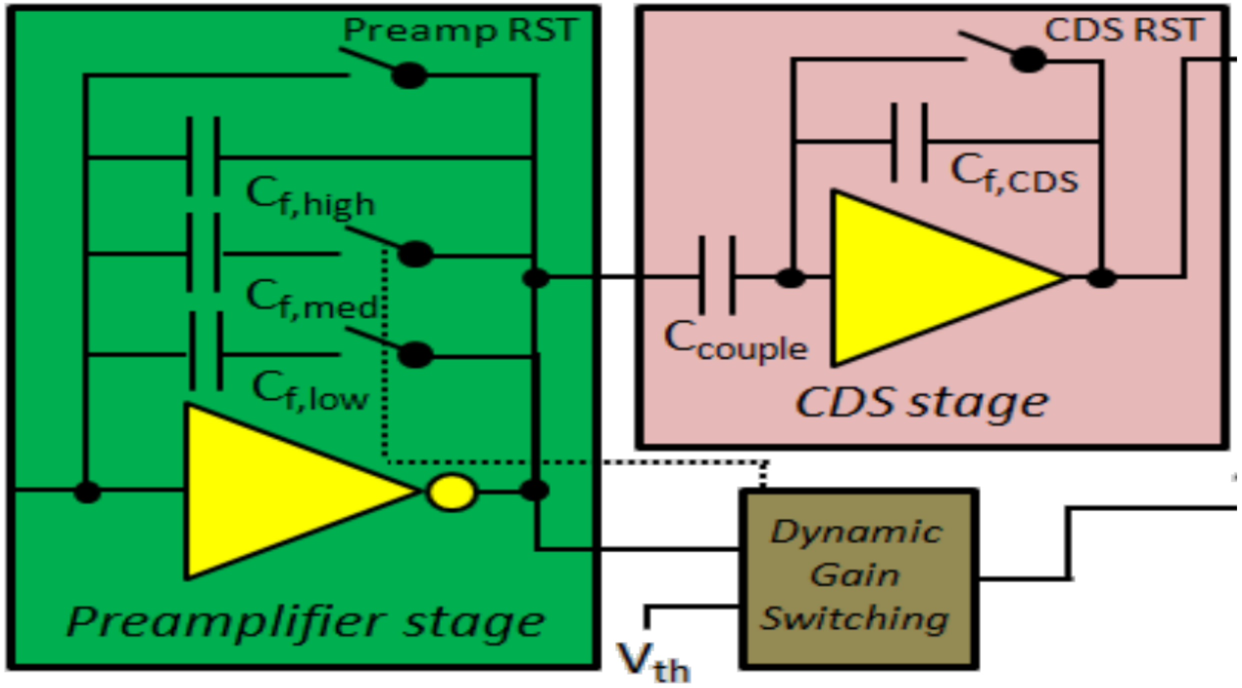
What Limits Dynamic Range?



- For Si, 10 keV x-ray deposits Q = (10,000eV /3.64) = 2740 e-
- $V_o = Q_{tot}$ /C1, i.e., Charge-to-voltage ratio proportional to 1/C1
- Noise ≈ 0.5 mV. Want good single x-ray sensitivity, say, S/N=5
- Set C1 so Q from 1 x-ray yields $V_o \geq$ 5x(0.5 mV) = 2.5 mV
- But CMOS voltage range ~ 3V => Dynamic range = 3V/2.5 mV = 1200

What methods are used to extend dynamic range without resorting to nonlinear response?

(1) Increase DR by dynamically changing C



$C_{high} = 60fF$

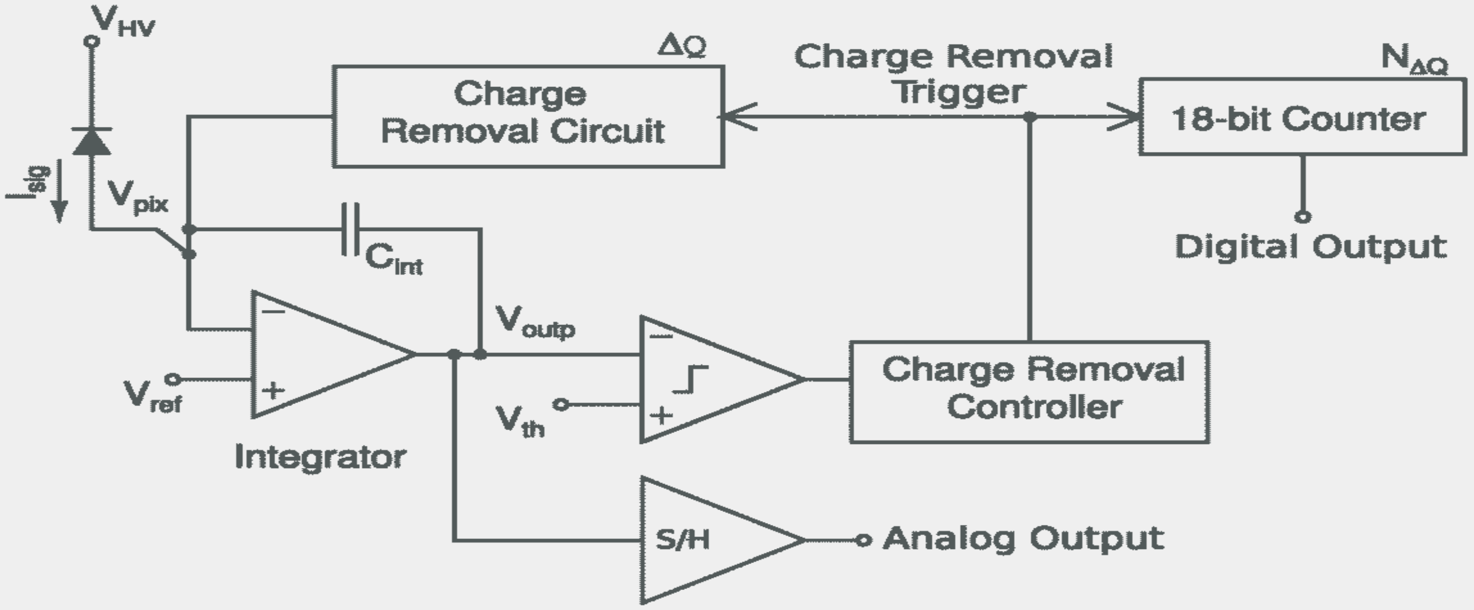
$C_{med} = 3pF$

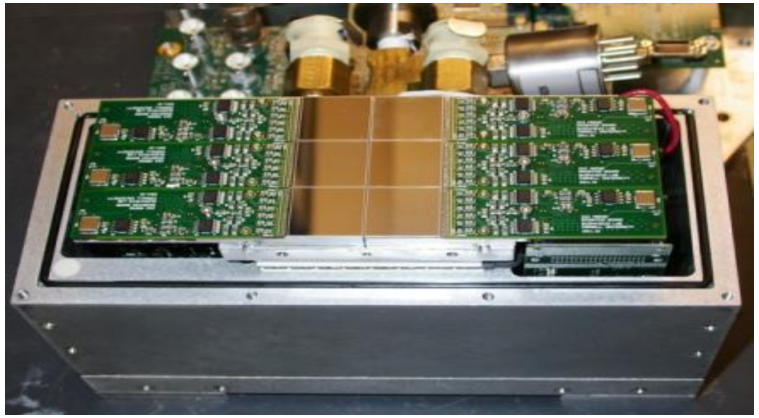
$C_{low} = 10pF$

- “Adaptive gain”
- Pioneered by SLS (GOTTHARD, JUNGFRAU, AGIPD)
- Dynamically monitor V_O
- As V_O approaches limit, add C_{med} , and, again, C_{low}
- DR = $2x10^4$ @ 8 keV

AGIPD image from http://photon-science.desy.de

(2) Dynamically remove charge (MM-PADs)





256x384 pixel MM-PAD-1.0
38TB/day @ 1.1 kHz

Read time/frame (continuously)	860 µs; 1.1 kHz framing, continuously
Read noise (RMS)	0.16 photons @ 8 keV
Dynamic range	4.7 x 10^7 photons/pix/frame @ 8 keV
Sustained count rate	>10^8 ph/pix/s
Instantaneous count rate	>> 10^{12} ph/pix/s (e.g. ~200 ph/pix/pulse)
Linearity	Excellent, because measures charge

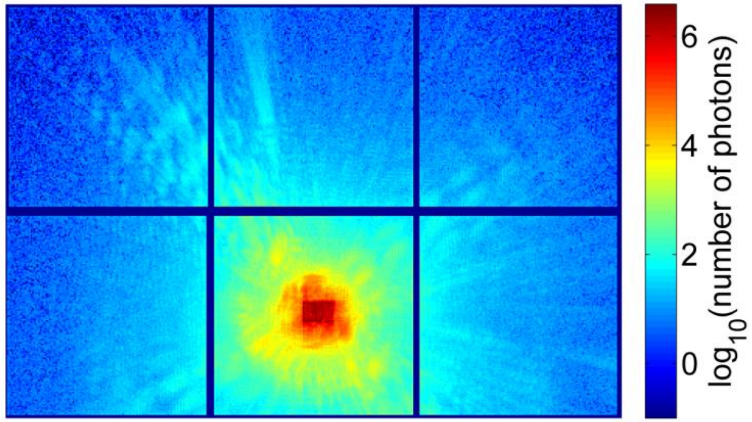
Tate et al., *J. Phys: Conf. Ser*. **25** (2013) 062004

MM-PAD: applications

Wide dynamic range gives **extraordinary experimental flexibility**

Coherent diffractive imaging

PETRA-III / Mancuso (Eu-XFEL)

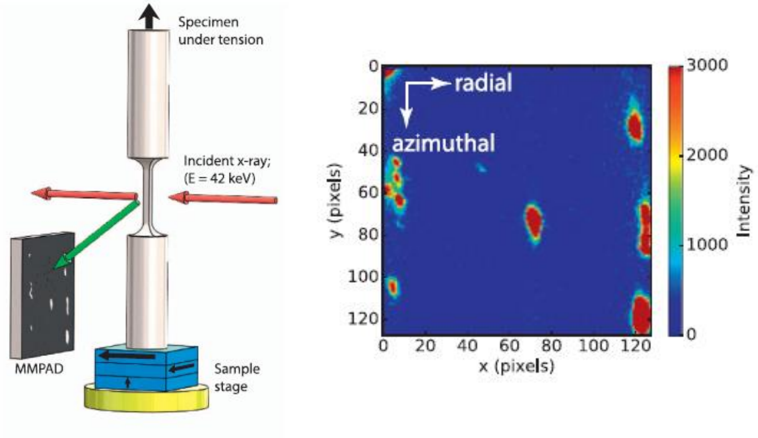


Giewekemeyer et al., *Journal of Synchrotron Radiation* (2014)

- Capture scattering pattern from Au test object, allowing ptychographic image reconstruction with ~25nm resolution
- **Key detector features:** wide dynamic range, fidelity at high incident photon rates (**>10^7 ph/pix/s** in central spot)

Deformation in metals

CHESS / Beaudoin (U. Illinois)

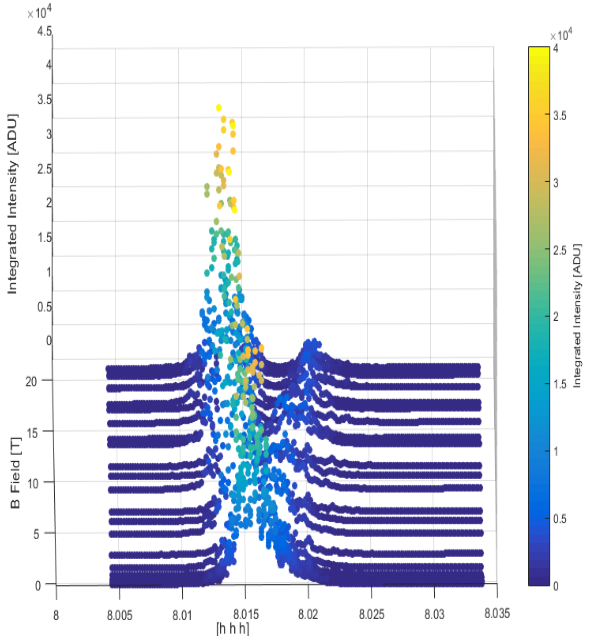


Chatterjee et al., *J. Mechanics & Physics of Solids* (2017)

- Probe grain-level deformation mechanisms and residual stress in polycrystalline Ti-7Al alloy under applied stress gradient
- **Key detector features:** CdTe sensor for efficient detection of 42 keV photons

Piezomagnetic ordering in UO2

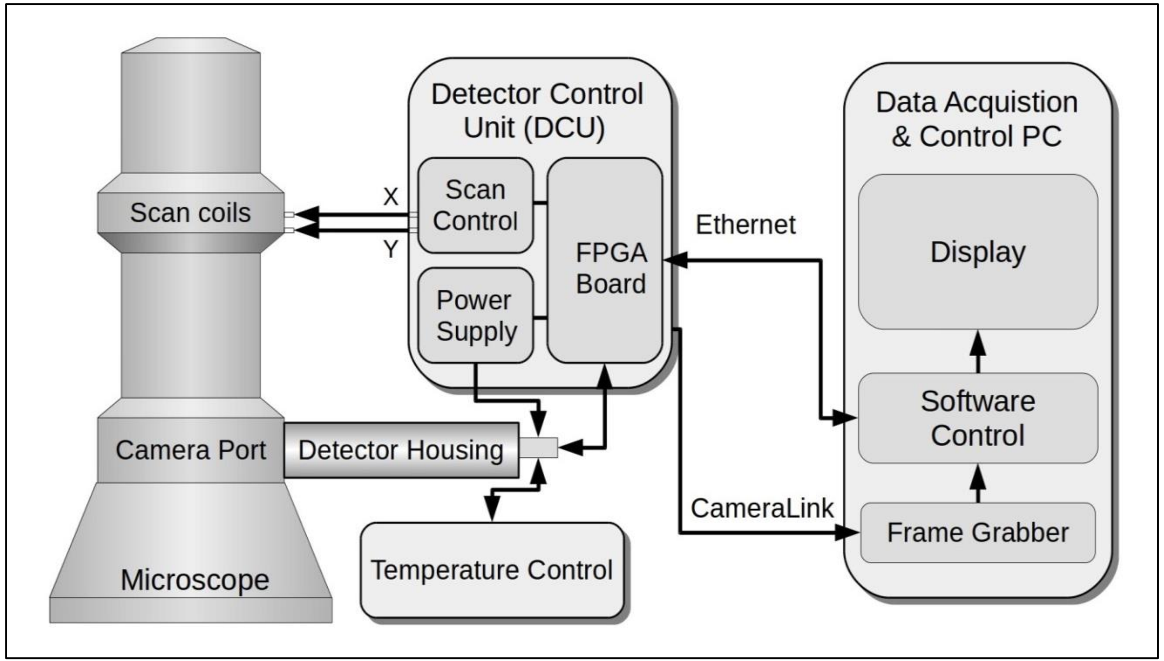
APS / Gofryk (Idaho Nat'l Lab)

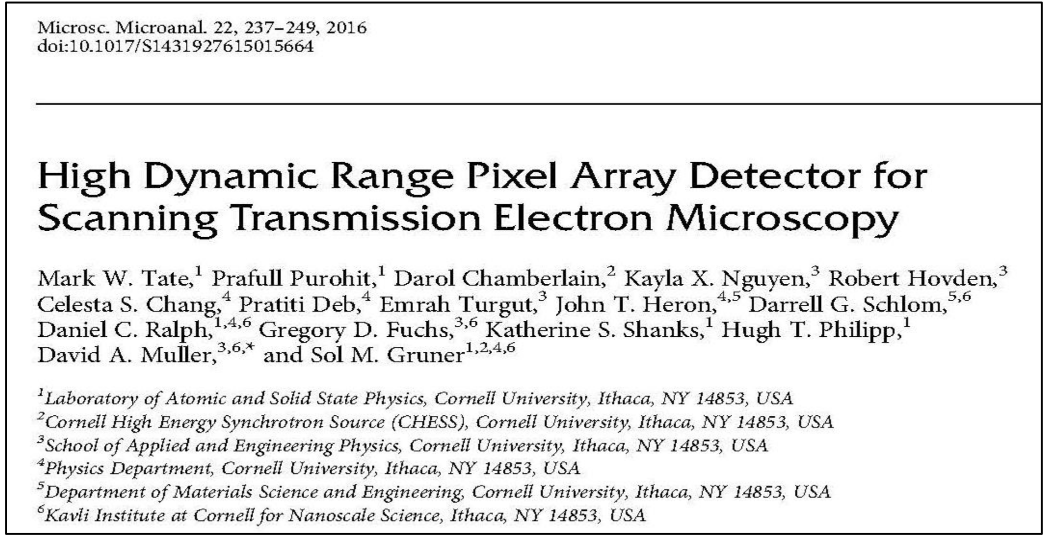


Antonio et al., *Nat. Communications Materials* (2021)

- Observe Bragg peak splitting in UO2 during 10ms magnetic pulse
- **Key detector features:** Fast (1 kHz) continuous frame rate

MM-PAD used in STEM (EM-PAD)




Microsc. Microanal. 22, 237–249, 2016
doi:10.1017/S1431927615015664

High Dynamic Range Pixel Array Detector for Scanning Transmission Electron Microscopy

Mark W. Tate,[1] Prafull Purohit,[1] Darol Chamberlain,[2] Kayla X. Nguyen,[3] Robert Hovden,[3] Celesta S. Chang,[4] Pratiti Deb,[4] Emrah Turgut,[3] John T. Heron,[4,5] Darrell G. Schlom,[5,6] Daniel C. Ralph,[1,4,6] Gregory D. Fuchs,[3,6] Katherine S. Shanks,[1] Hugh T. Philipp,[1] David A. Muller,[3,6,*] and Sol M. Gruner[1,2,4,6]

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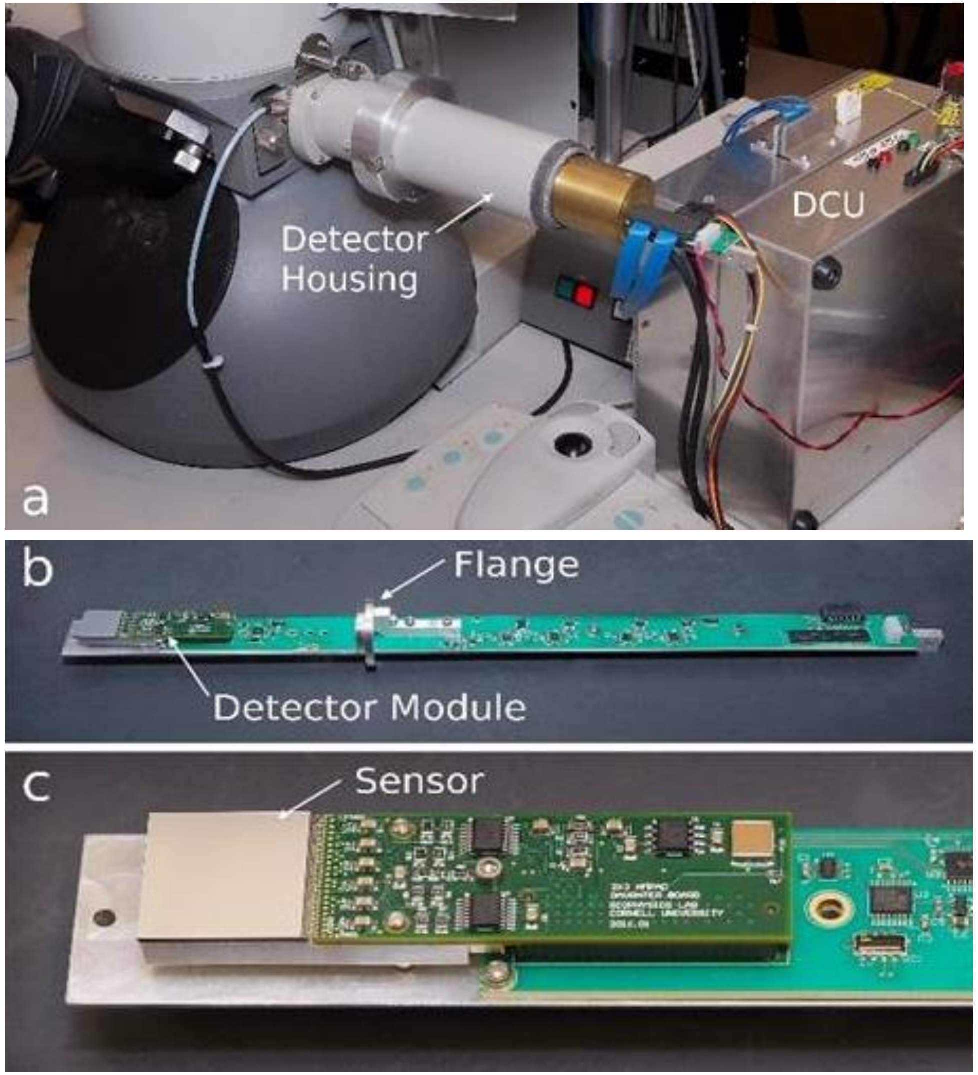
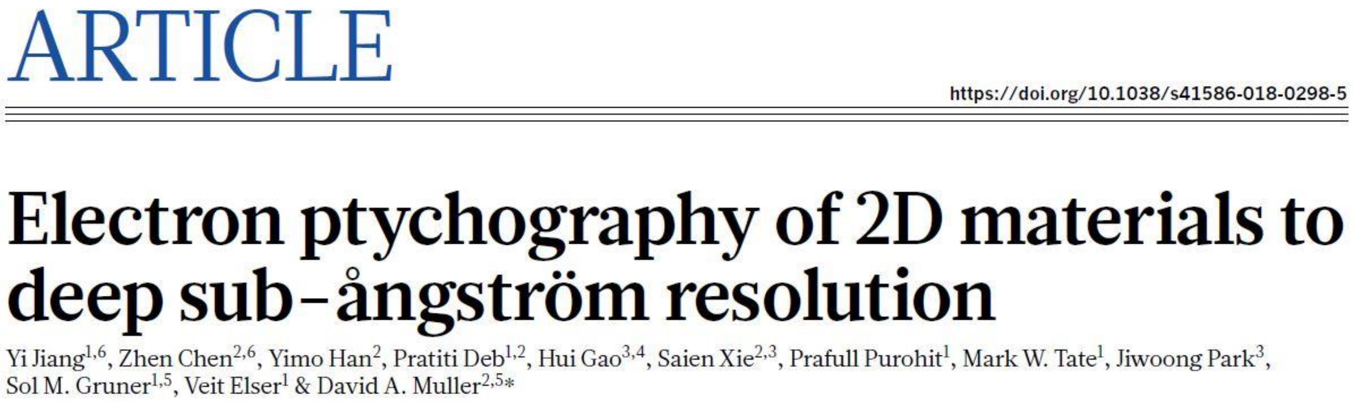
[6] *Kavli Institute at Cornell for Nanoscale Science, Ithaca, NY 14853, USA*



128x128 pixel EM-PAD has been commercialized by Thermo Fisher

Ptychography with EM-PAD

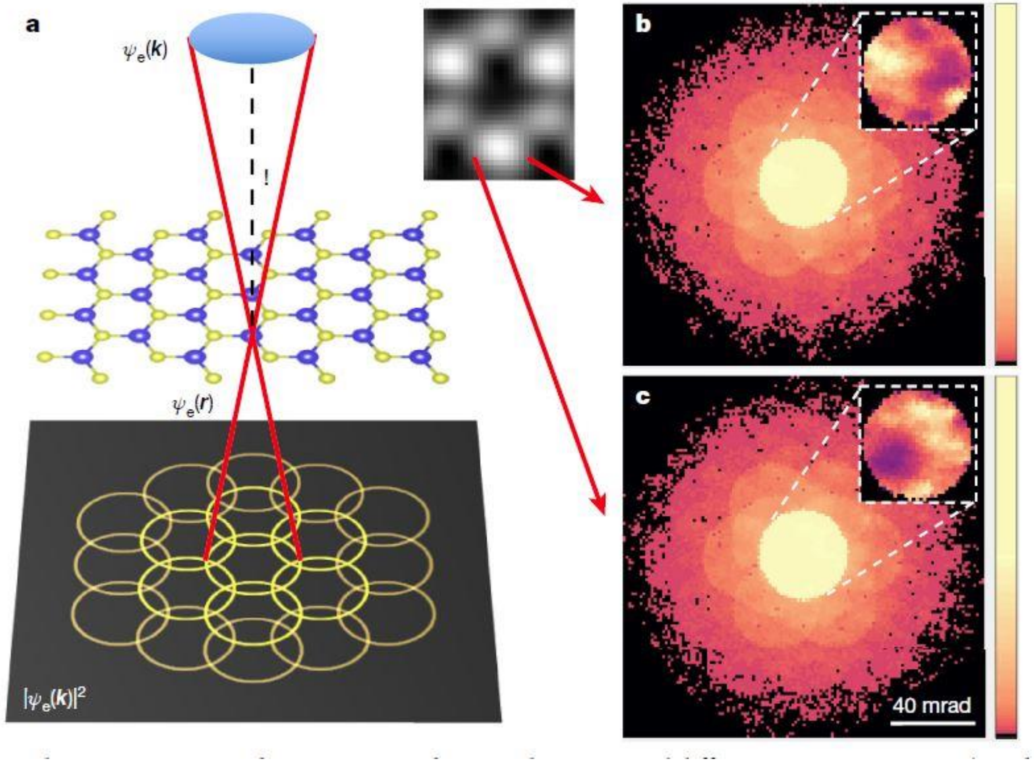


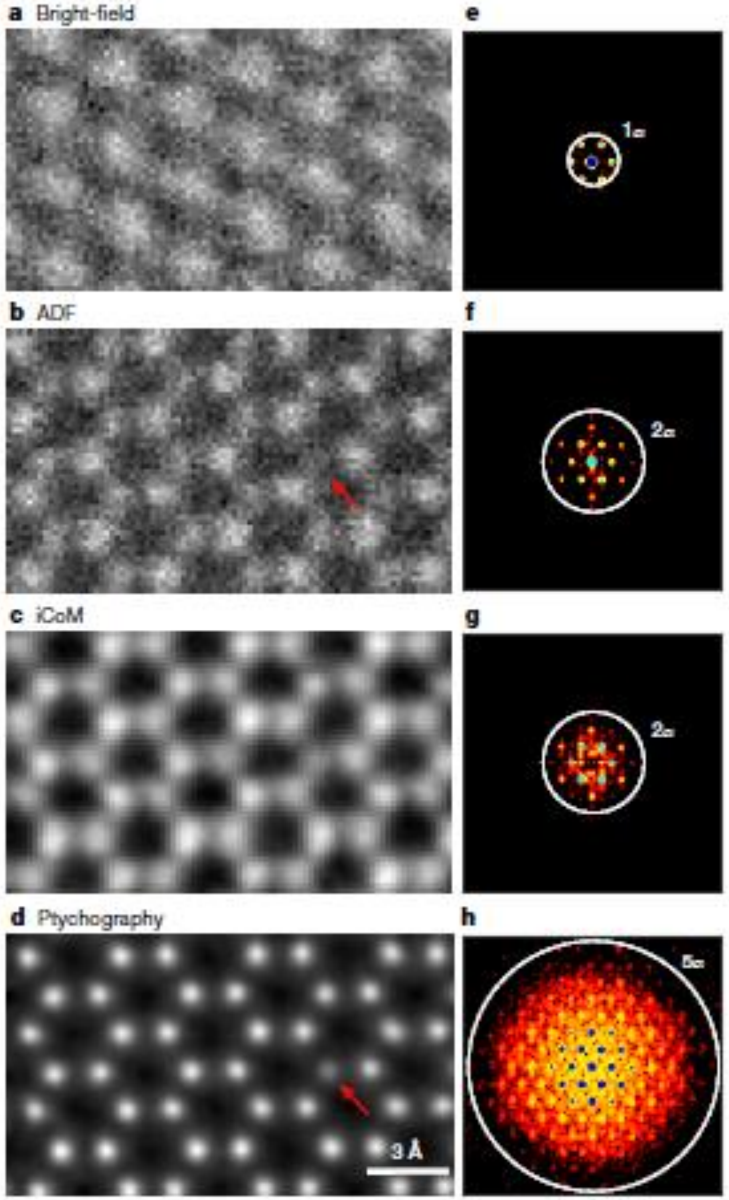
ARTICLE

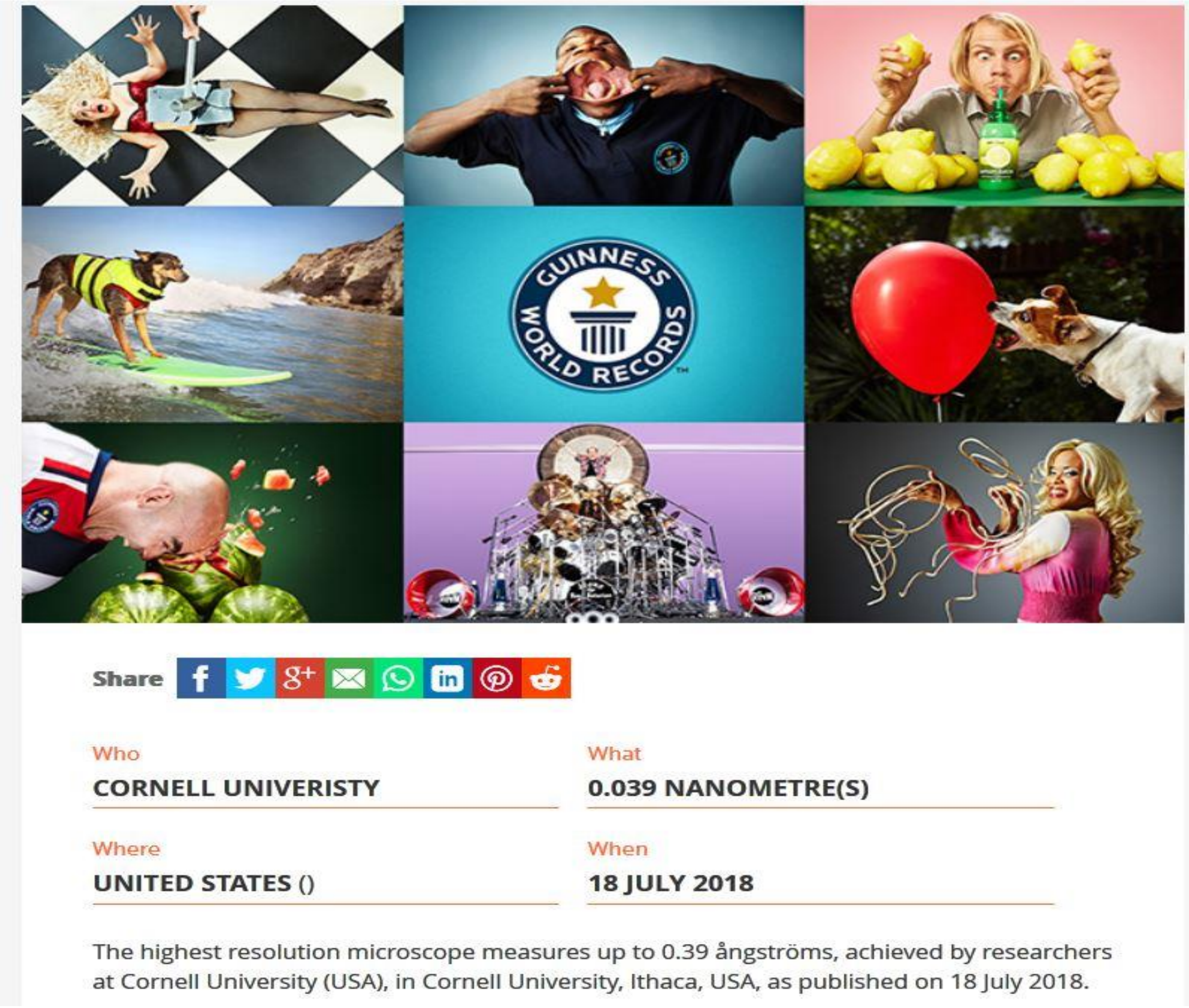
https://doi.org/10.1038/s41586-018-0298-5

Electron ptychography of 2D materials to deep sub-ångström resolution

Yi Jiang[1,6], Zhen Chen[2,6], Yimo Han[2], Pratiti Deb[1,2], Hui Gao[3,4], Saien Xie[2,3], Prafull Purohit[1], Mark W. Tate[1], Jiwoong Park[3], Sol M. Gruner[1,5], Veit Elser[1] & David A. Muller[2,5]*







Who
CORNELL UNIVERISTY

What
0.039 NANOMETRE(S)

Where
UNITED STATES ()

When
18 JULY 2018

The highest resolution microscope measures up to 0.39 ångströms, achieved by researchers at Cornell University (USA), in Cornell University, Ithaca, USA, as published on 18 July 2018.

Cornell/APS MM-PAD-2.1

- Update to MM-PAD-1.0 design
- Collaboration with detector group at APS
  - APS: firmware, support electronics
  - Cornell: ASIC

Specification	**MM-PAD-1.0** **(8 keV equivalent units)**	**MM-PAD-2.1 target** **(20 keV equivalent units)**
# of pixels per chip	128 x 128	
Pixel size	150 µm	
Sensor	Si	CdTe
Electron-collection capability?	No – holes only	Yes – collect electrons or holes
Frame rate	1.1 kHz	$\geq$1.1 kHz
Duty cycle	0% at max frame rate	$\geq$ 90%
Read noise	0.16 photon	$\leq$ 0.1 photon
Well capacity	4.7×10^7 photons	10^8 photons
Instantaneous photon rate	> 10^{12} ph/s/pix	> 10^{12} ph/s/pix
Sustained photon rate	> 10^8 ph/s/pix	> 10^9 ph/s/pix

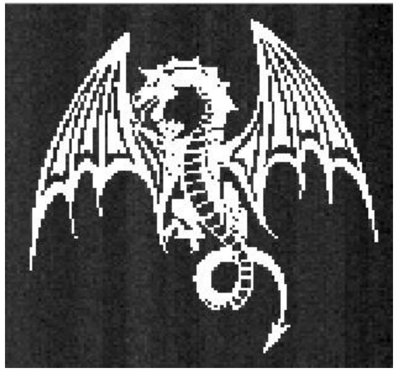
MM-PAD-2.1 full-scale system

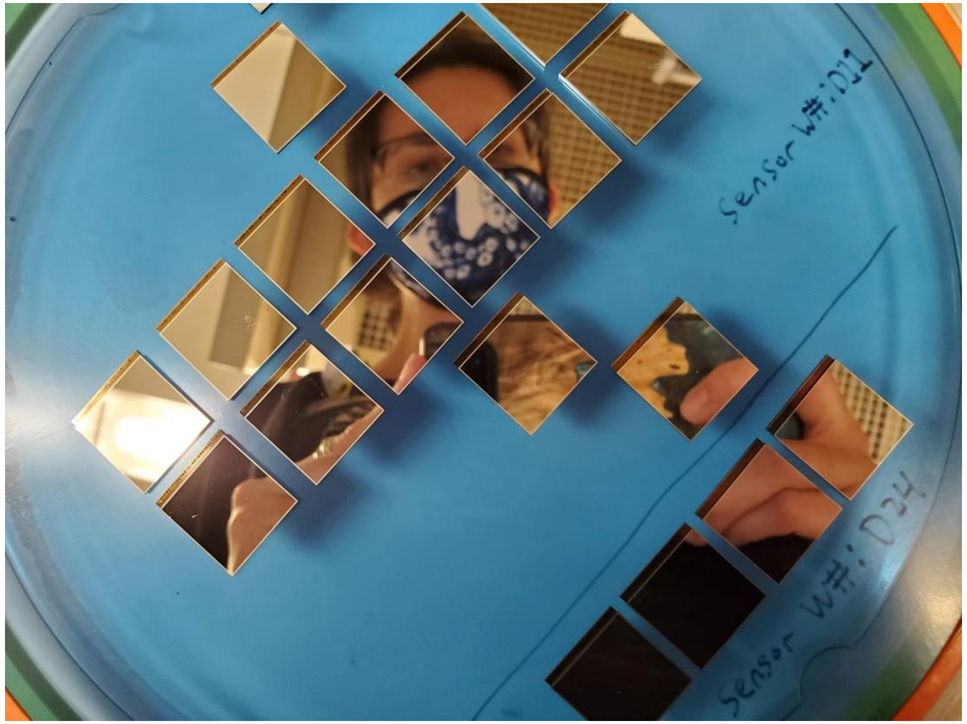
- Single-chip Si, CdTe hybrids have been assembled, and x-ray testing is underway

- Four 256x384 pixel systems planned: 2 at Cornell, 2 at APS

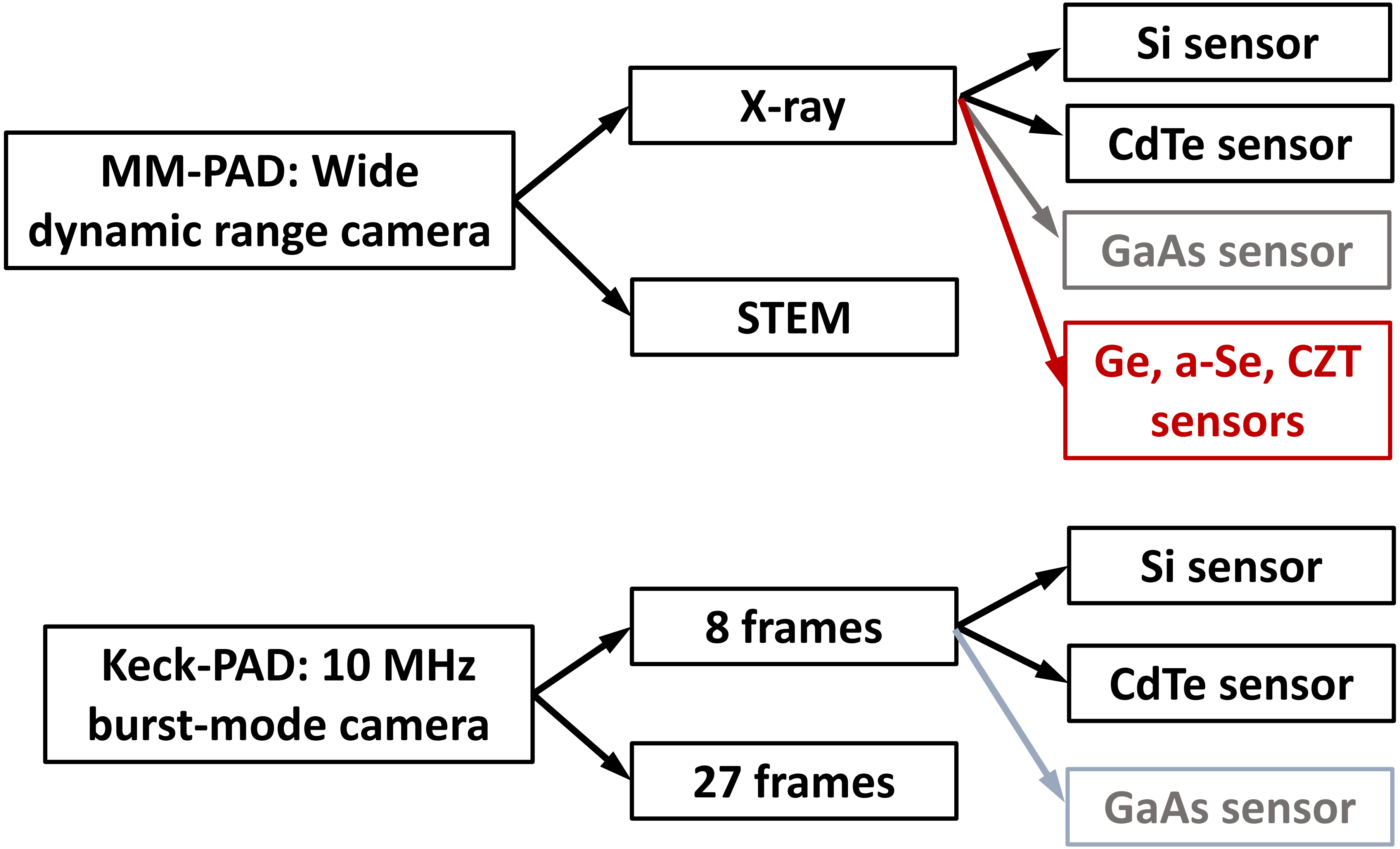
- Selectable readout of full array at continuous frame rate of **1.6 kHz** or 128x128 pixel area at **9 kHz**

128x128 pixel test pattern





Two families of integrating detectors



MM-PAD: Wide dynamic range camera

X-ray

STEM

Si sensor

CdTe sensor

GaAs sensor

Ge, a-Se, CZT sensors

Keck-PAD: 10 MHz burst-mode camera

8 frames

27 frames

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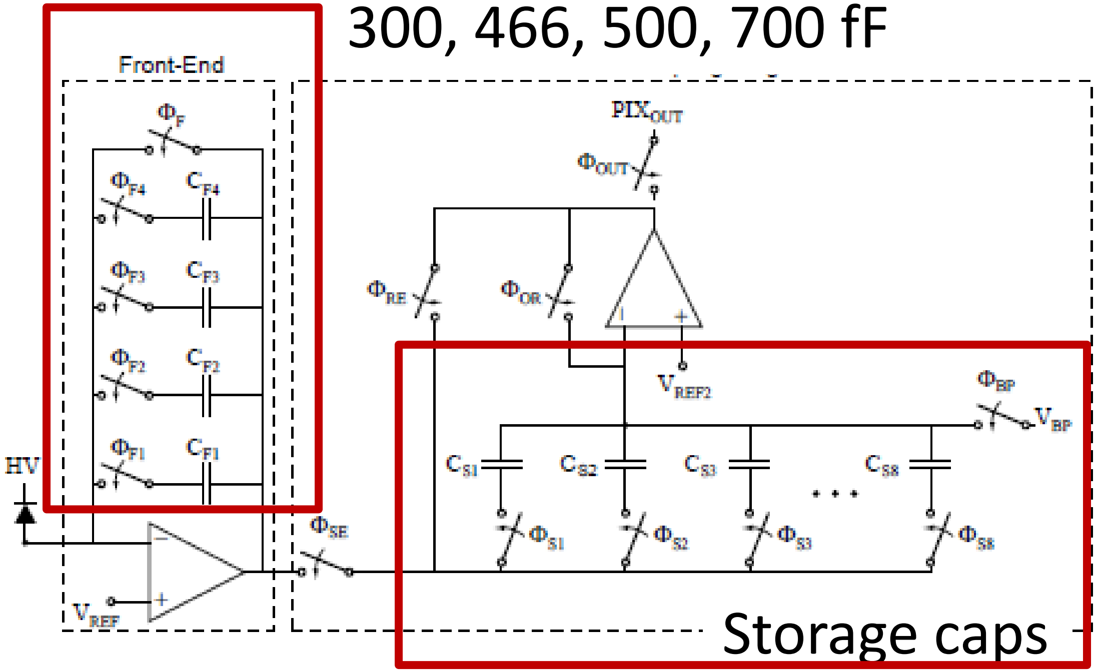
Both families: 150 µm x 150 µm pixel size, 256 x 384 pixel tiled systems assembled @ Cornell

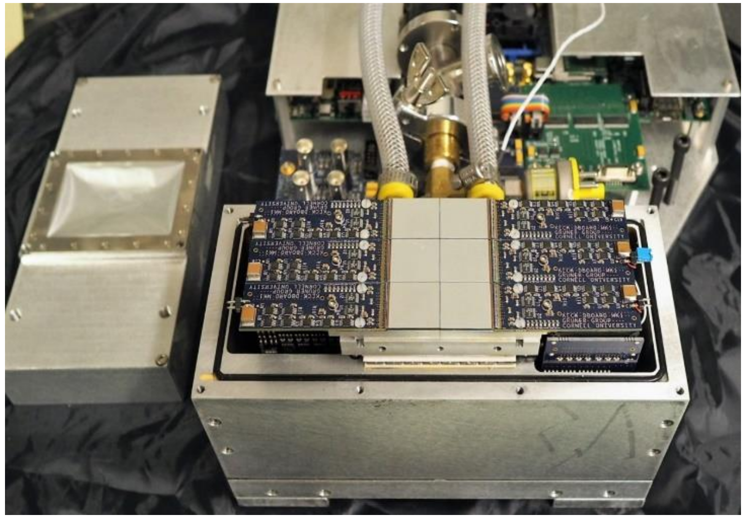
Keck-PAD

Integration caps - 300, 466, 500, 700 fF



Storage caps

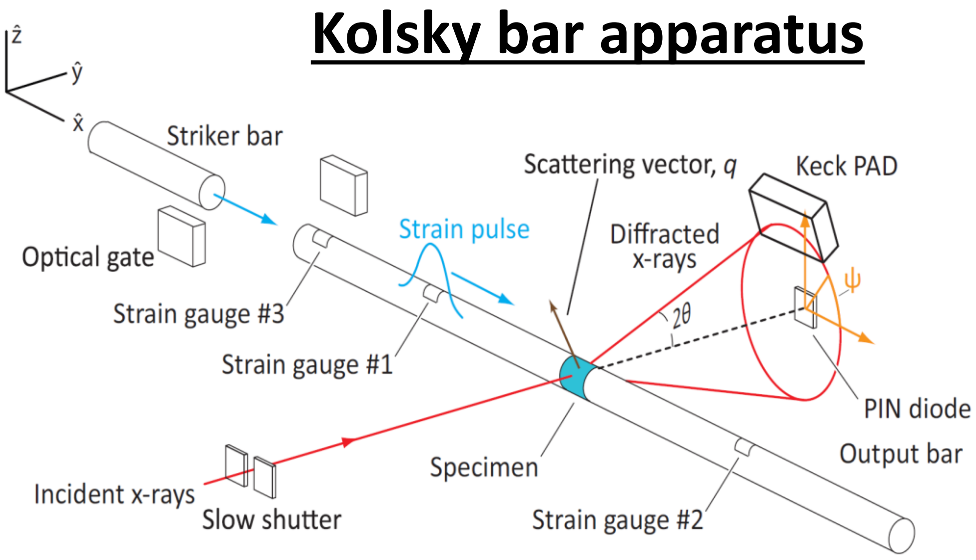
In-pixel frame storage provides down to ~**100 ns spacing between stored frames (~10 MHz)**



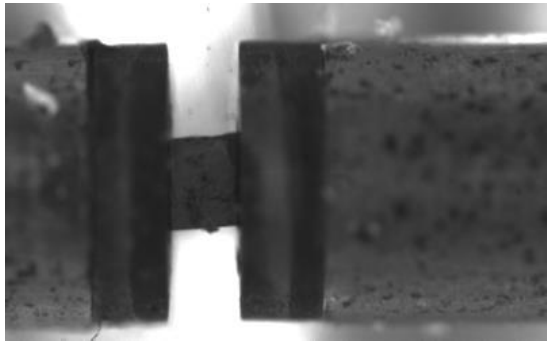
Read time	0.86 ms/frame
Storage caps/pixel	8
Read noise	1 photon @ 8 keV (C_F = 300 fF) 4 photons @ 8 keV (C_F = 1966 fF)
Well capacity	1112 photons @ 8 keV (C_F = 300 fF) 7288 photons @ 8 keV (C_F = 1966 fF)

Keck-PAD: Microsecond dynamics

Deformation of metal compounds under high strain rates

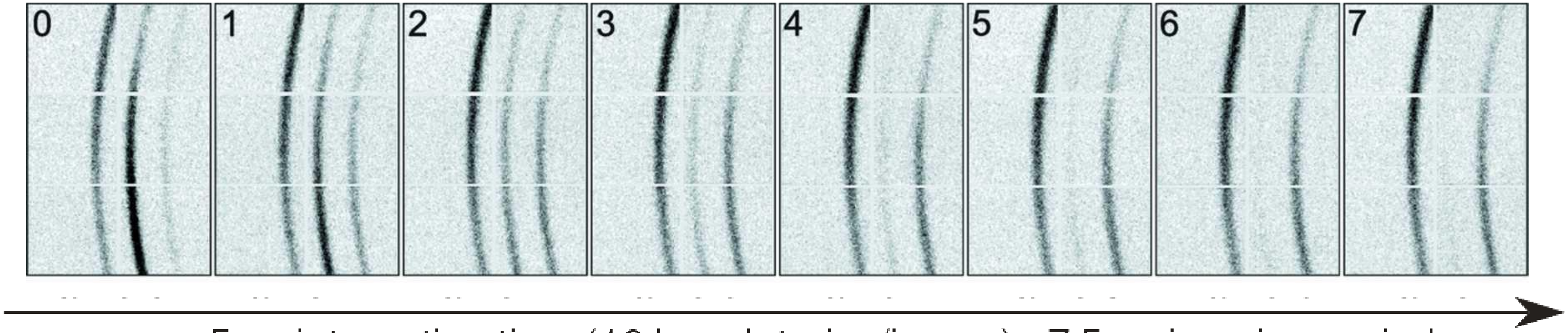


Husted *et al., Journal of Dynamic Behavior of Materials* (2018)



Optical video, 1 million FPS

- CHESS G3 with Hufnagel group @ Johns Hopkins & Army Research Office
- Key detector features:
    - **Fast frame rate**
    - **Good single-photon SNR**



5 us integration time (10 bunch trains/image) , 7.5 us imaging period

Summary

- **MM-PAD architecture successfully extends Dynamic Range**
- **Proving to be scientifically successful**
- **The community is starting to reap the benefits of Cornell’s MM-PAD development program**
- **Commercial variants exist and next generation variants are well along in the development pipeline**

Thanks!

Slides (mostly) from
Julia Thom-Levi,
Sol Gruner,
Kate Shanks

Pixel2022

The Tenth International Workshop
on Semiconductor Pixel Detectors for Particles and Imaging

12–16 December 2022
La Fonda Hotel | Santa Fe, New Mexico, USA

TOPICS:
Pixel detectors in nuclear and particle physics, astrophysics, bioscience, and x-ray science, with emphasis on pixel sensor technology and device design, front-end readout electronics, radiation effects on devices, mechanics and integration, calibration, and data processing.

Stipends are available for partial support of students and postdocs attending this conference.
For information on how to apply for a stipend: physics.unm.edu/Pixel2022/stipends.php

Contributed abstracts for talks and posters are welcome.
Deadline for abstract submission: September 15, 2022.

NSF
DEPARTMENT OF PHYSICS & ASTRONOMY
U.S. DEPARTMENT OF ENERGY
Organizing Committee

TO REGISTER, AND FOR MORE INFO:
physics.unm.edu/Pixel2022

CONTACT:
pixel2022@unm.edu