CHESS facility report and detector development at Cornell

IFDEPS Virtual Thursdays 2021
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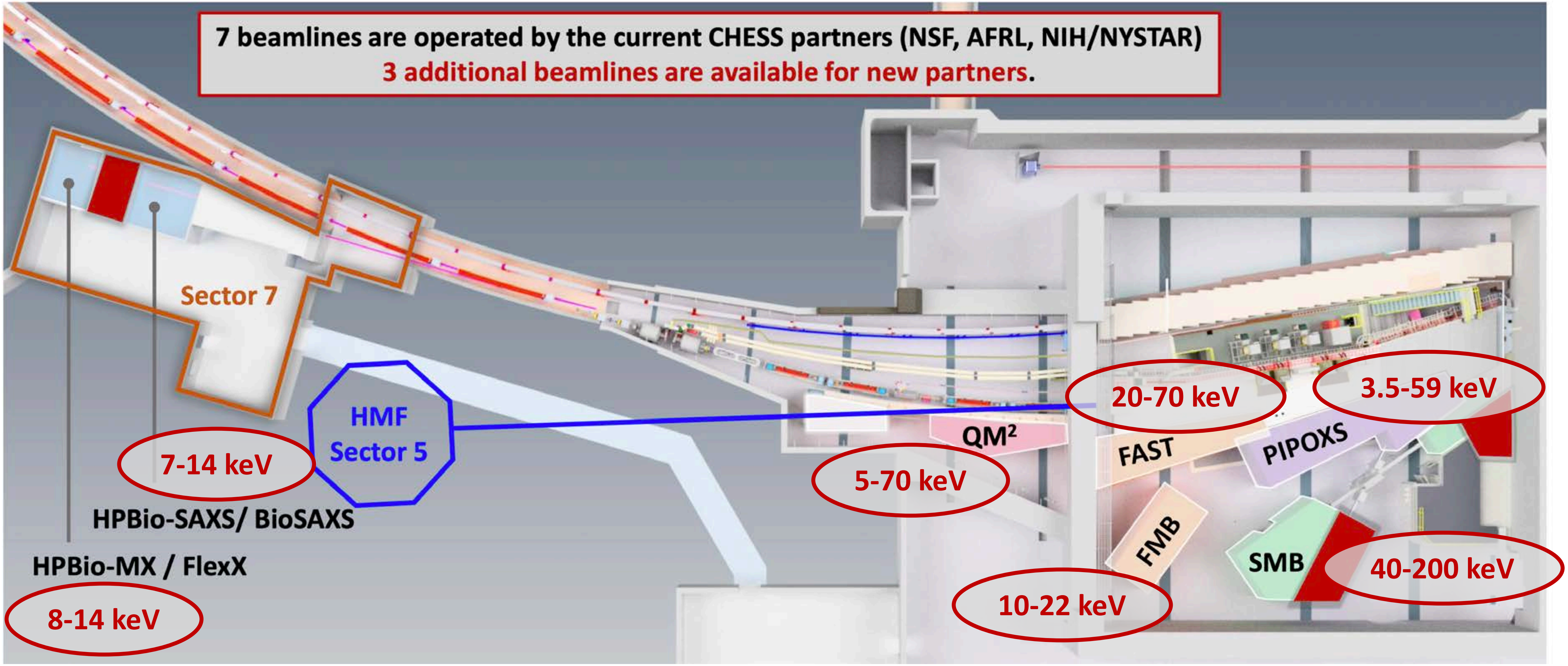
March 25, 2021

Cornell High Energy Synchrotron Source (CHESS)



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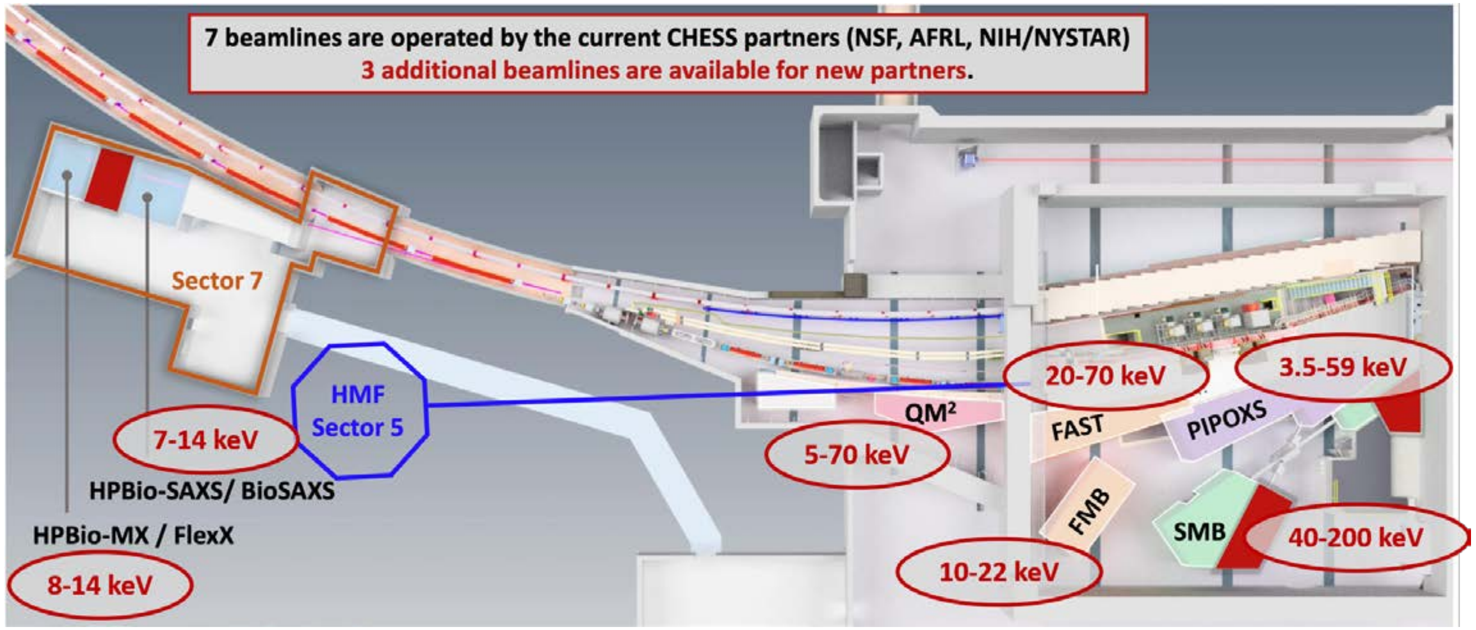


Detector needs at CHESS:

- Support for imaging, scattering, and spectroscopic techniques
- Efficient detection of **high-energy x-rays** (especially **>20 keV**)
- **Large area** detectors to support certain scattering techniques (e.g. high-energy diffraction microscopy, protein crystallography, …)
- **Wide dynamic range** to make full use of increased source brilliance, and to support seamless data collection of dynamic signals
- **Fast frame rates** to support time-resolved experiments
- Movement towards on-the-fly data processing to help users **wrangle large datasets**

Detector activity at Cornell and CHESS

Detectors in active circulation at CHESS (a non-comprehensive list):

- Lens-coupled CMOS/CCDs – primarily for imaging: Andor Neo, Retiga 4000DC
- Large-area flat-panel detectors – primarily for scattering: Dexela 2923, GE RT41
- Pixel array detectors: Eiger 1M, Eiger 500k CdTe, many Pilatus incarnations, CdTe PIXIRAD, CdTe MM-PAD
- Energy-resolving detectors: Vortex SDDs, Si-sensor Maia

Detector development:

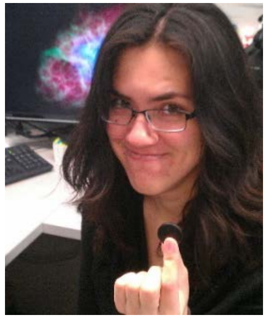
- Largely seated in the Gruner/Thom-Levy group
- External collaborations: Argonne, BNL, SLAC, Sydor Instruments, Thermo Fisher, MIT-LL, …
- **Frame rate** and **dynamic range** are major design focuses
- Additional focus: training students and post-docs


Sol Gruner

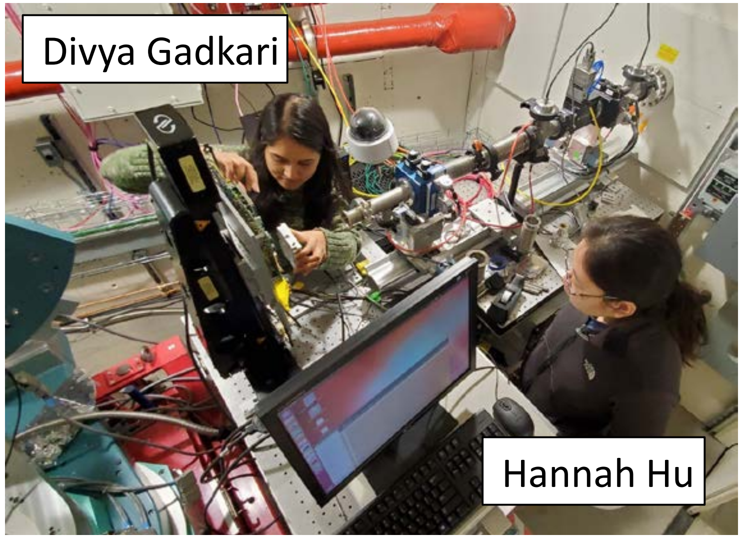

Julia Thom-Levy


Mark Tate

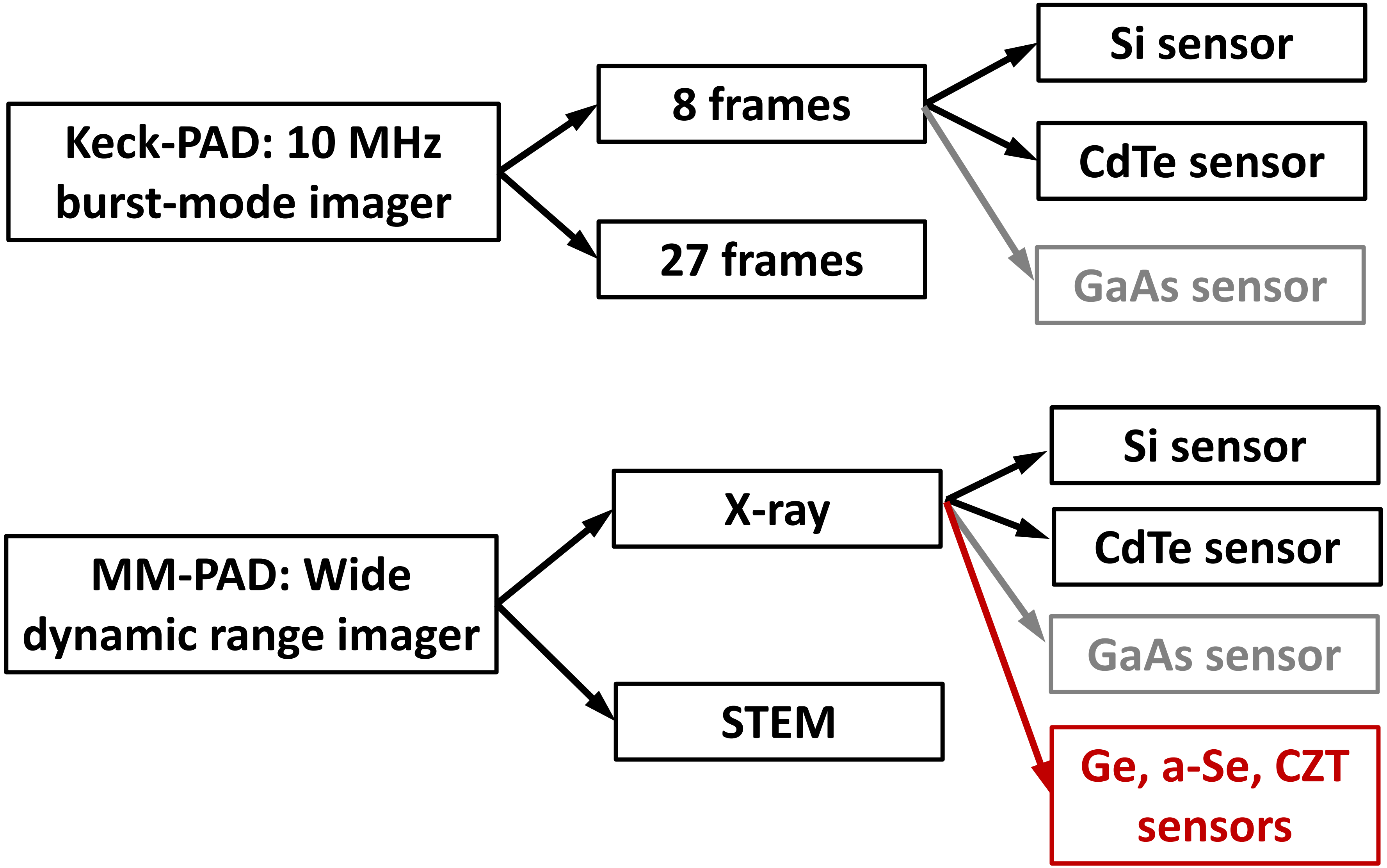

Hugh Philipp


Kate Shanks


Marty Novak

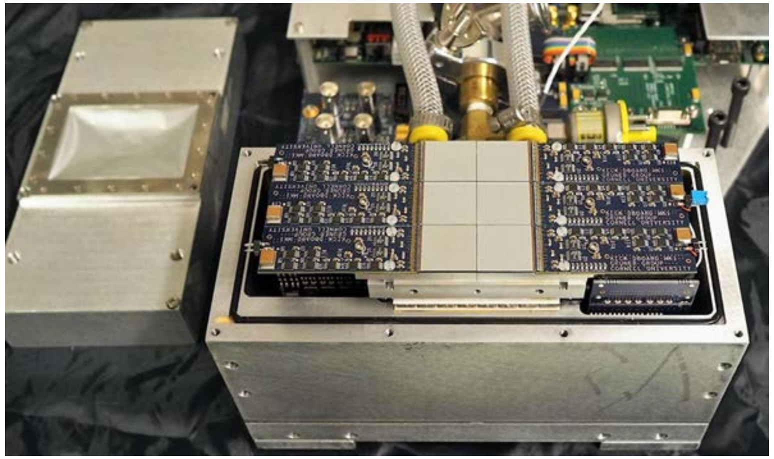


Two Families of Integrating Detectors



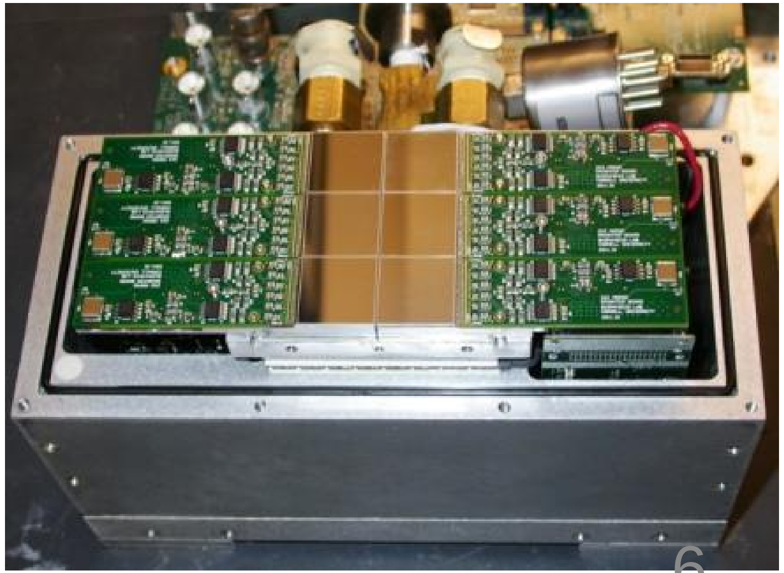
Keck-PAD (up to 10 MHz)

Read time (burst mode)	150 ns separation between stored frames; readout: 860 µs/stored frame
Storage caps/pixel	8
Read noise	1 photon @ 8 keV (high gain) 4 photons @ 8 keV (low gain)
Well capacity	~1100 8-keV photons (high gain) ~ 7300 8-keV photons (low gain)



MM-PAD 1.0 (up to 1.1 kHz)

Read time (continuously)	860 µs/frame -> 1.1 kHz continuous
Read noise (RMS)	0.16 photons @ 8 keV
Well capacity	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

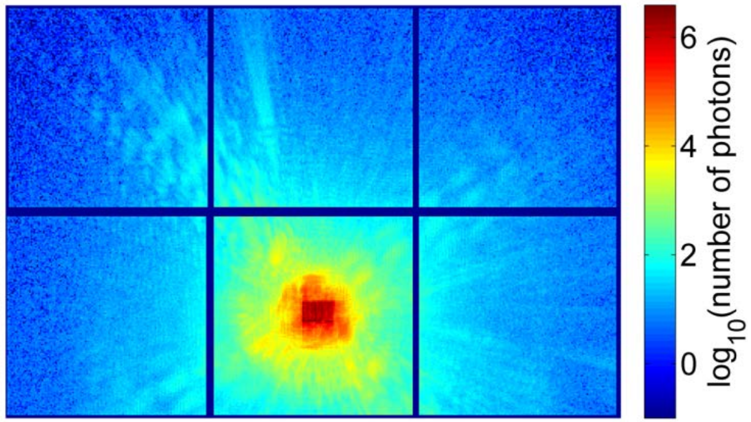


MM-PAD: applications

Wide dynamic range gives **extraordinary experimental flexibility**

Coherent diffractive imaging

PETRA-III / Mancuso (Eu-XFEL)

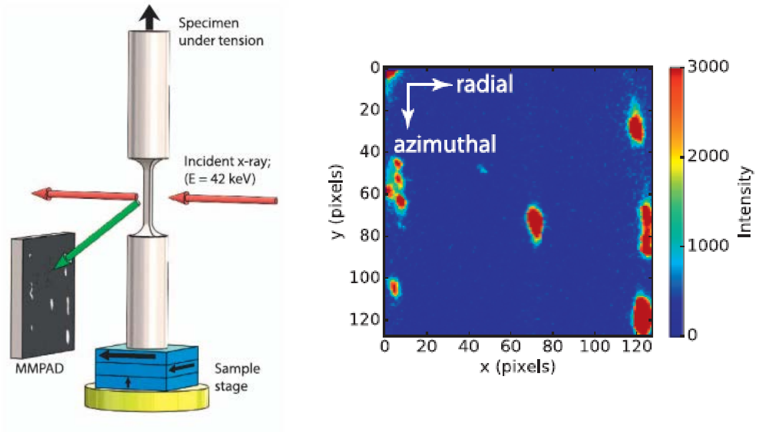


Giewekemeyer et al., *Journal of Synchrotron Radiation* (2014)

- 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)

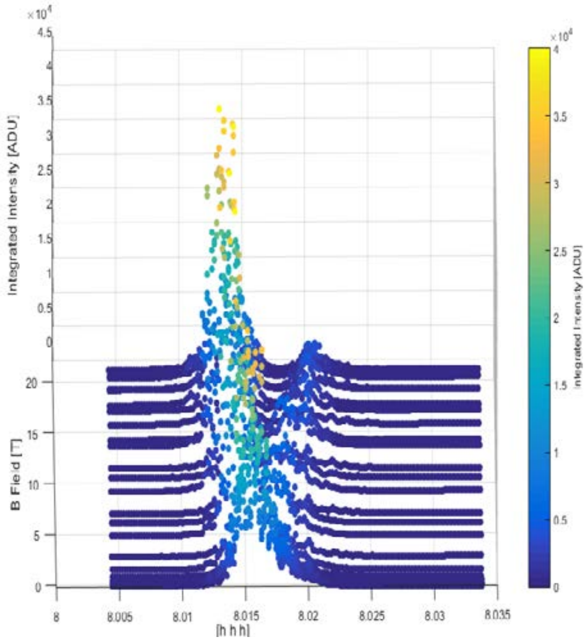


Chatterjee et al., *J. Mechanics & Physics of Solids* (2017)

- 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

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

128x128 pixel test pattern

- 128x128 pixel full-scale ASIC fabricated in early 2020
  - Modifications for reduced read noise
  - June 2020: ASIC confirmed functional using in-pixel test sources

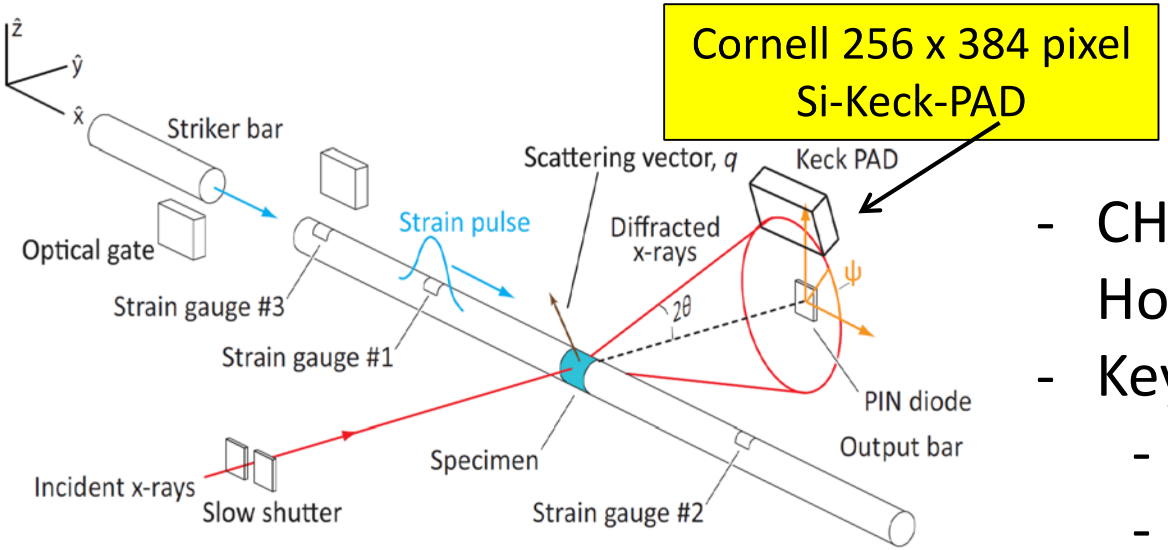
- Single-chip Si, CdTe hybrids have been assembled, and x-ray testing is underway

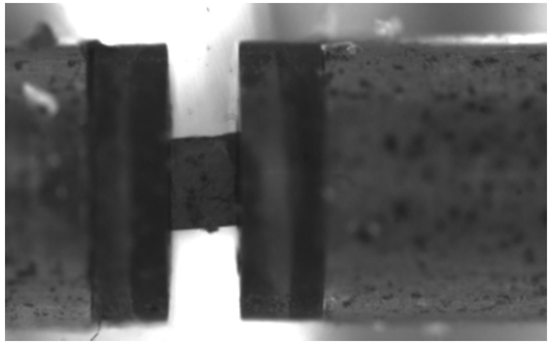
- Four 256x384 pixel systems planned: 2 at Cornell, 2 at APS

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

Keck-PAD: Microsecond dynamics

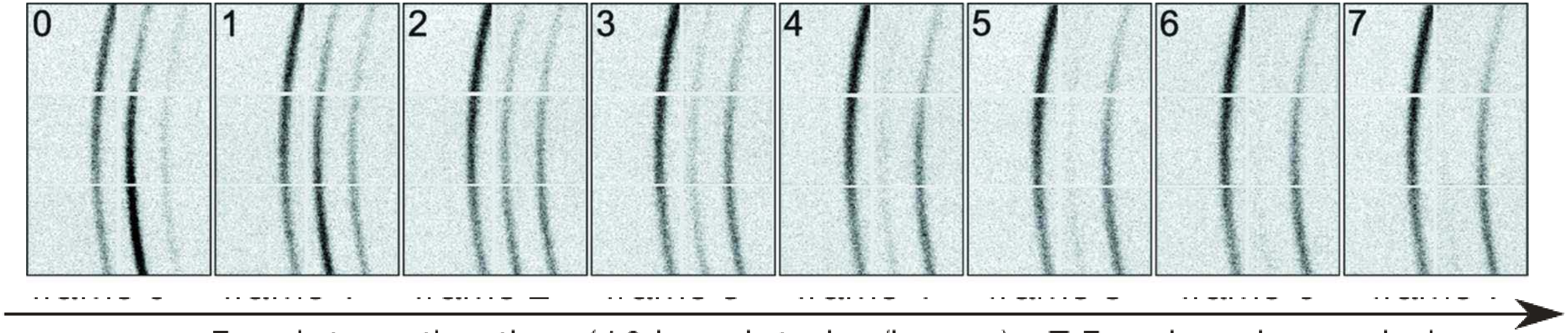
Deformation of metal compounds under high strain rates





Optical video, 1 million FPS

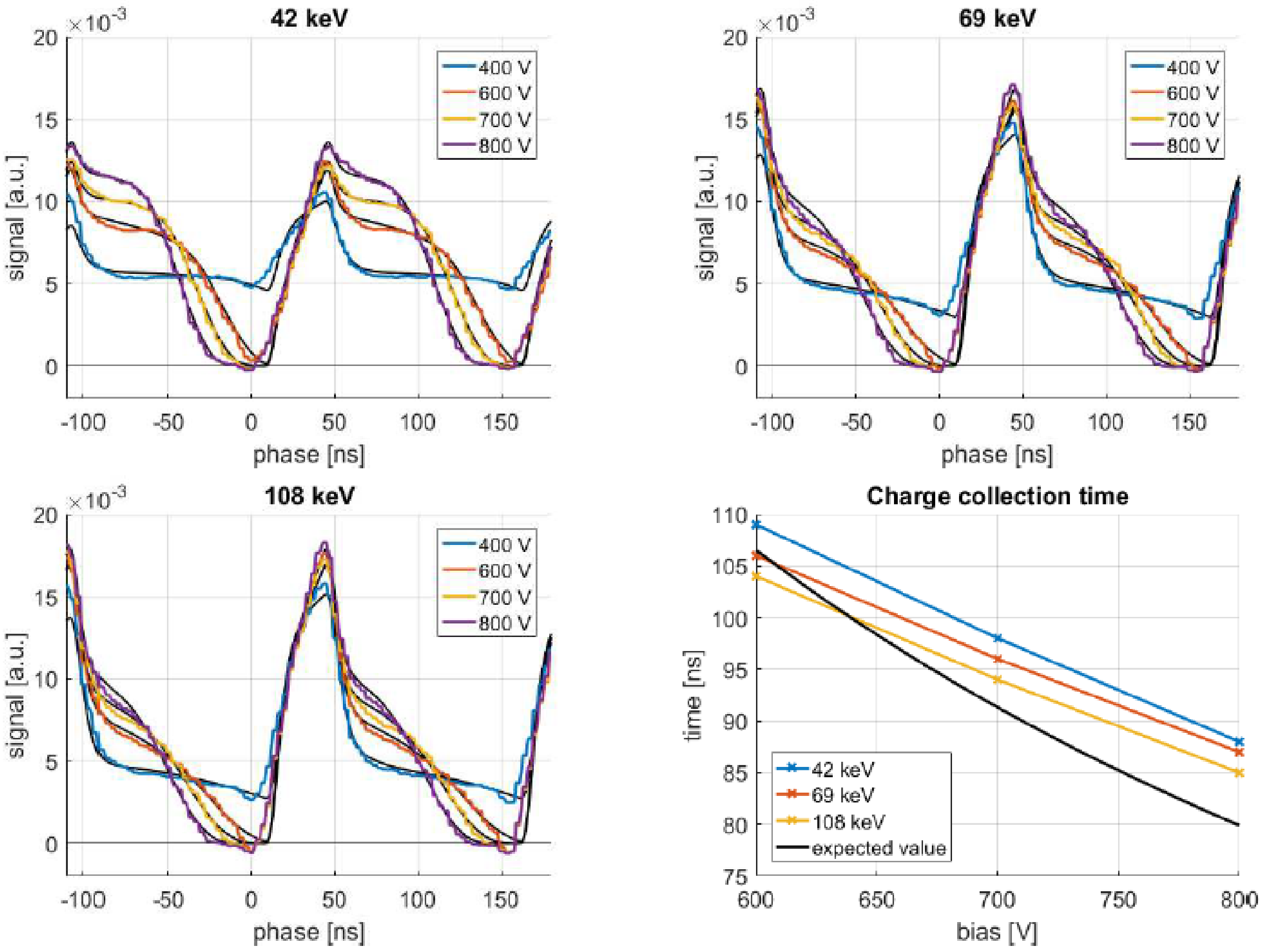
- CHESS G3 with Hufnagel group @ Johns Hopkins & Army Research Office
- Key detector features:
    - **Fast frame rate**
    - **Good single-photon SNR**



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

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

Single bunch imaging at 153 ns with CdTe



Becker et al., *JINST* **12** (2017) P06022

Beamline: APS 35ID-E (DCS) – 153 ns bunch separation

Energy: 7.1 keV fundamental, with harmonics up to >120 keV

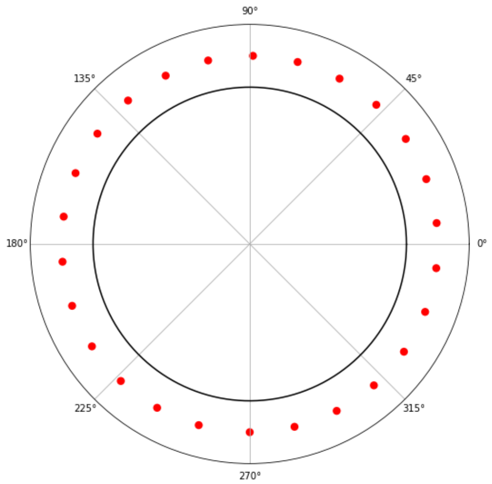
Measure isolated diffraction spots from copper foil

Measured response (solid) in excellent agreement with drift & diffusion simulations (dotted)

Charge collection times ~100 ns are feasible with 750 μm thick CdTe

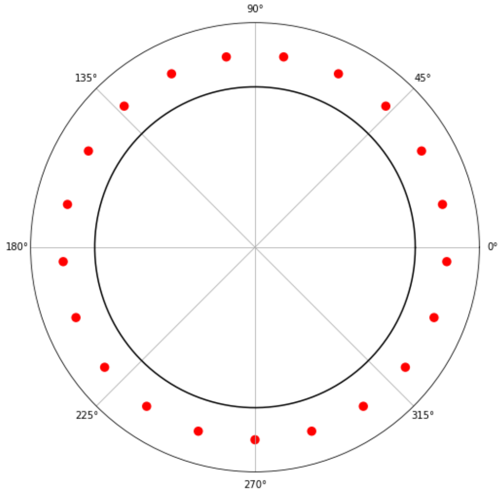
Proposed CHESS fill patterns for single-bunch experiments

98ns mode



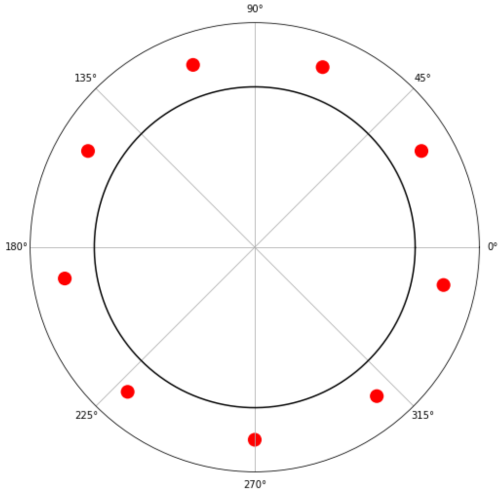
26 bunches, 98 ns separation

21-bunch mode



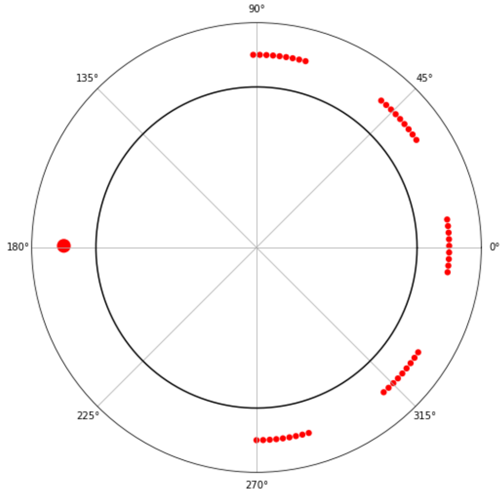
21 bunches, 122 ns separation

9-bunch mode



9 bunches, 280 ns separation

Hybrid-singlet mode



Train separation 182 ns, singlet isolated by > 600 ns

Keck-PAD speeds

Pixel	possible	possible	✓	✓
Si	✓	✓	✓	✓
CdTe	x	✓	✓	✓

Ongoing and future work

- High-Z alternatives to CdTe are under active investigation
- Larger-format (512 x 512 pixel, 1k x 1k pixel) variants of Keck and MM-PAD are being built and commercialized by Sydor Technologies
- MM-PAD-2.1 system development to achieve full-frame, continuous 10 kHz operation
- Next-generation MM-PAD ASIC development goals: increased radiation hardness, on-chips DACs for bias generation, frame rates beyond 10 kHz, …
- Exploring concepts for on-the-fly data reduction/processing in firmware

Thank you!

- Detector development funding: U.S. DOE, DTRA, NIH, Keck Foundation, Kavli Foundation
- CHESS funding: NSF, Air Force Research Department, NIH, NYSTAR