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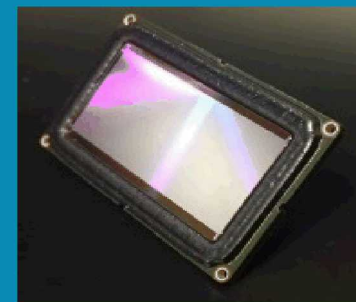

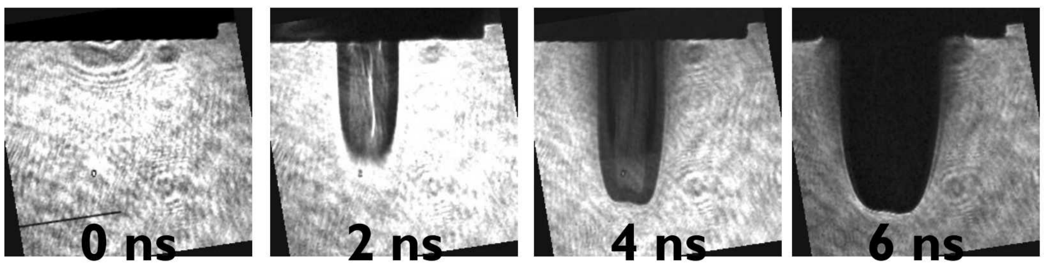

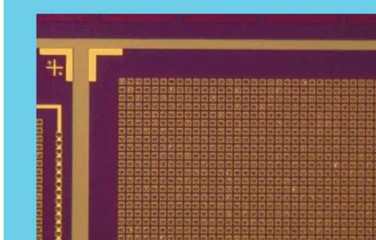

Q. Looker, A. P. Colombo, A. D. Edens, M. W. Kimmel, J. W. Stahoviak, M. O. Sanchez, L. D. Claus, M. G. Wood, G. A. Rochau, J. L. Porter

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Outline

The Ultrafast X-Ray Imager program at Sandia National Laboratories

- 2-D x-ray imagers with ~nanosecond gate times designed and fabricated at SNL
- Fielded at Z Machine, NIF, Omega, SLAC, …

Applications at Sandia's Z Machine

- Gated radiography
- Time-resolved spectroscopy
- Multi-frame x-ray imaging

Characterization Methods

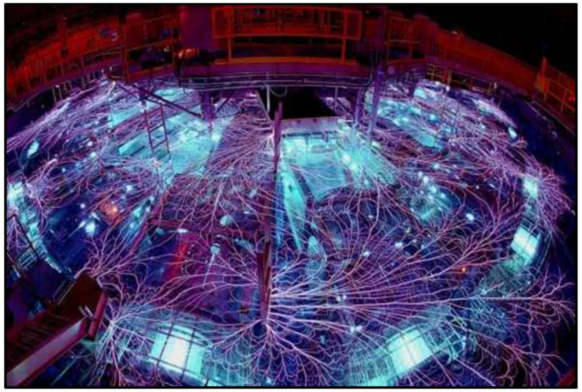
- Temporal gate profiles
- Linearity of response
- Application-specific configuration testing

Sensor improvements

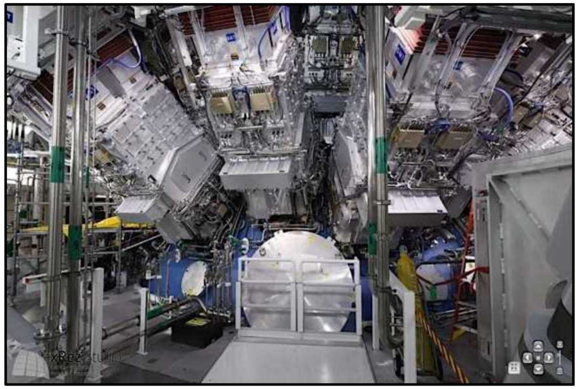
- ROIC improvements to reduce gate time, number of frames, …
- Superlattice enhancement for soft x-rays, electrons
- Thicker Si detectors and GaAs detectors

The Ultrafast X-Ray Imager Program at Sandia National Laboratories

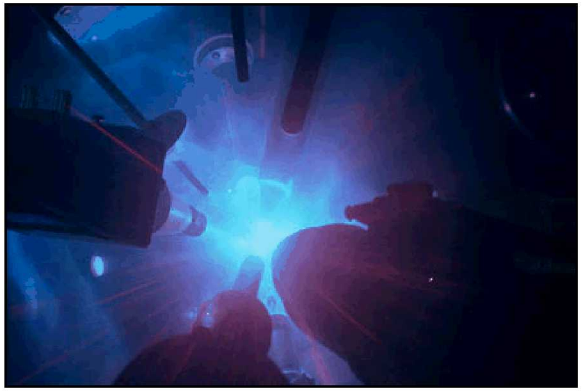
The UXI program at Sandia has created a new class of 2D, nanosecond-gated x-ray imagers



Z-Machine

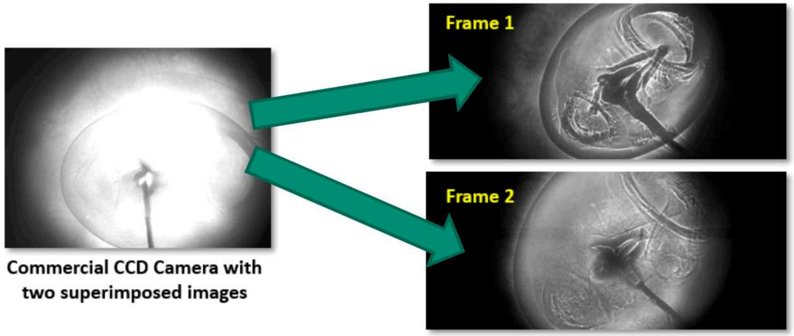


National Ignition Facility



Omega

- X-ray imaging is a valuable diagnostic for Inertial Confinement Fusion (ICF) and High Energy Density (HED) physics research
- Faster frame-rate reduces motion blur while multiple frames provide a temporal history of an evolving experiment
- Burst-mode CMOS imagers provide unique capability for multiple x-ray images on single line of sight with nanosecond gate times

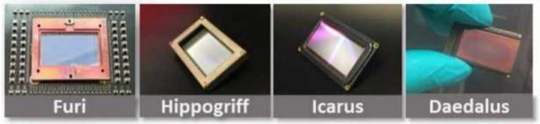


Commercial CCD Camera with two superimposed images

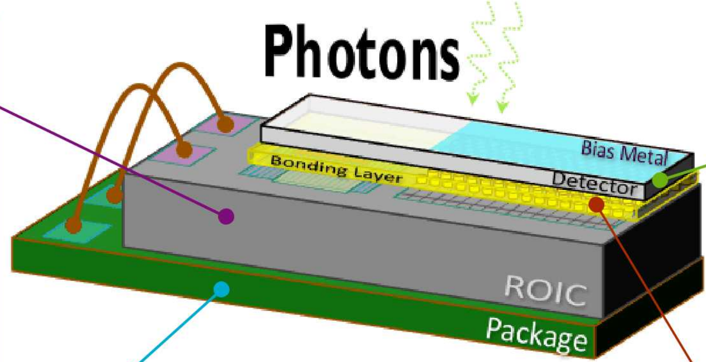
Furi Sensor 2ns shutters for both frames

Many parts come together to become a hybrid CMOS UXI camera

Readout Integrated Circuit (ROIC)

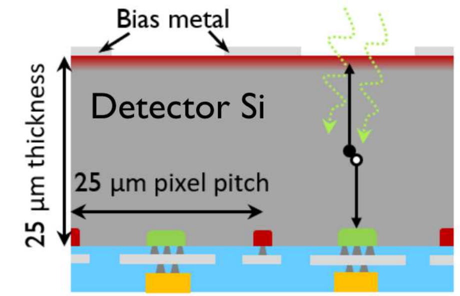


- Fabricated in SNL's 6" 350nm CMOS
- 1-2ns min shutter, 2-8 frames
- 1024x512 array of 25μm x 25μm pixels
- Adjustable shutter timing

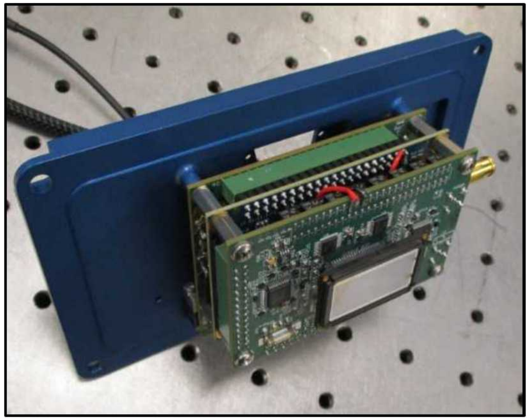


Hybrid CMOS Sensor

Detector Array



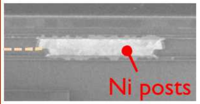
Package



UXI Camera System Development for Application-Specific Needs

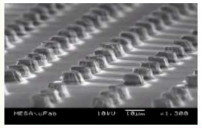
Integration

Direct Bond Interconnect (DBI)



- External supplier
- Wafer-to-wafer bond

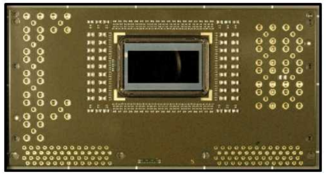
Indium bump

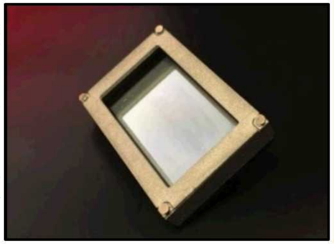


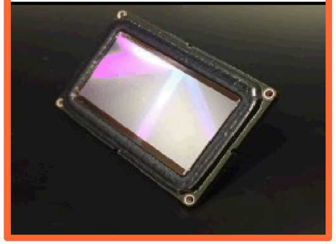
- Processing at Sandia
- Die-level processing

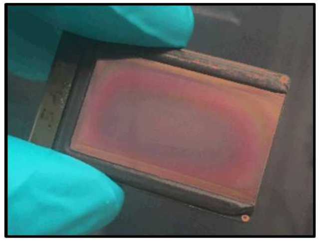
Icarus is the state-of-the-art sensor in an advancing product line

	In Use			In Test
	Furi	Hippogriff	Icarus	Daedalus
Year	FY14	FY15	FY16	FY19
Min Integration time	~1.5 ns	~2 ns	~1.5 ns	~1.0 ns
Frames	2	2 (full resolution) 4 or 8 (Row interlaced)	*4 (full resolution) *8 (L/R interlaced)	3 (full resolution) 6+ (Row/L/R interlacing)
Tiling Option	No	No	No	One Side
CMOS Process	350 nm (SNL)	350 nm (SNL)	350 nm (SNL)	350 nm (SNL)
Pixels	448 x 1024	448 x 1024	512 x 1024	512 x 1024
Pixel Size	25 µm x 25 µm	25 µm x 25 µm	25 µm x 25 µm	25 µm x 25 µm
Capacitor Full Well	1.5 million e^-	1.5 million e^-	0.5 million e^-	1.5 million e^-



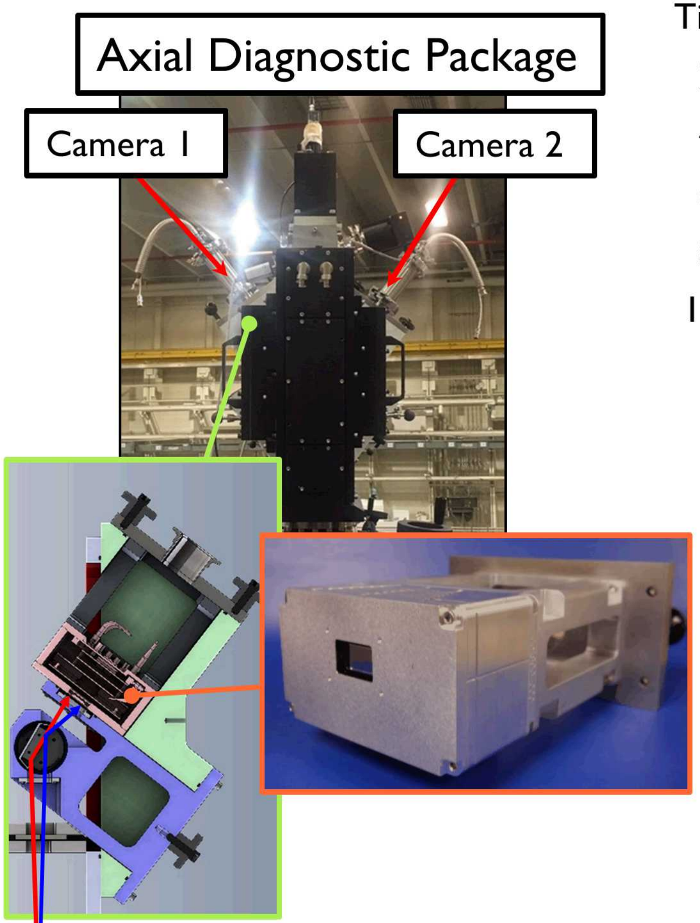




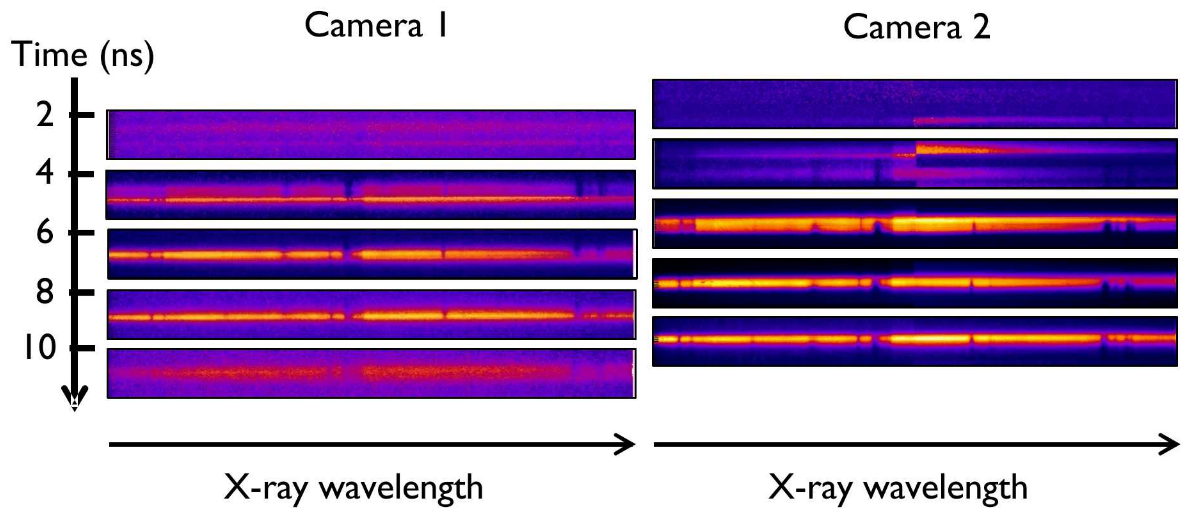


Applications at Sandia's Z Machine

Dual UXI cameras are now being used for 16-frame spectroscopy



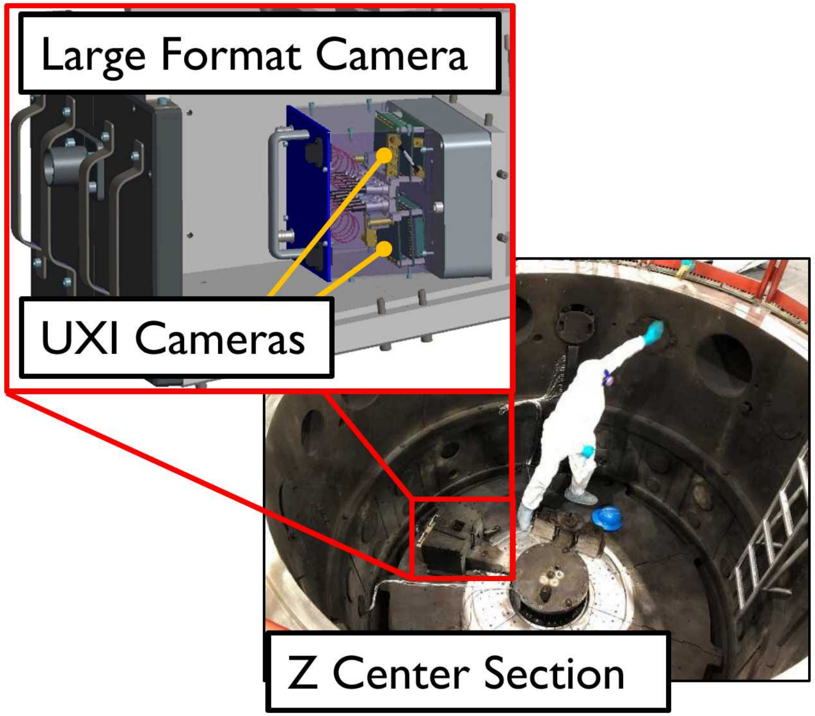
Crystal reflector disperses x-ray energy in one dimension

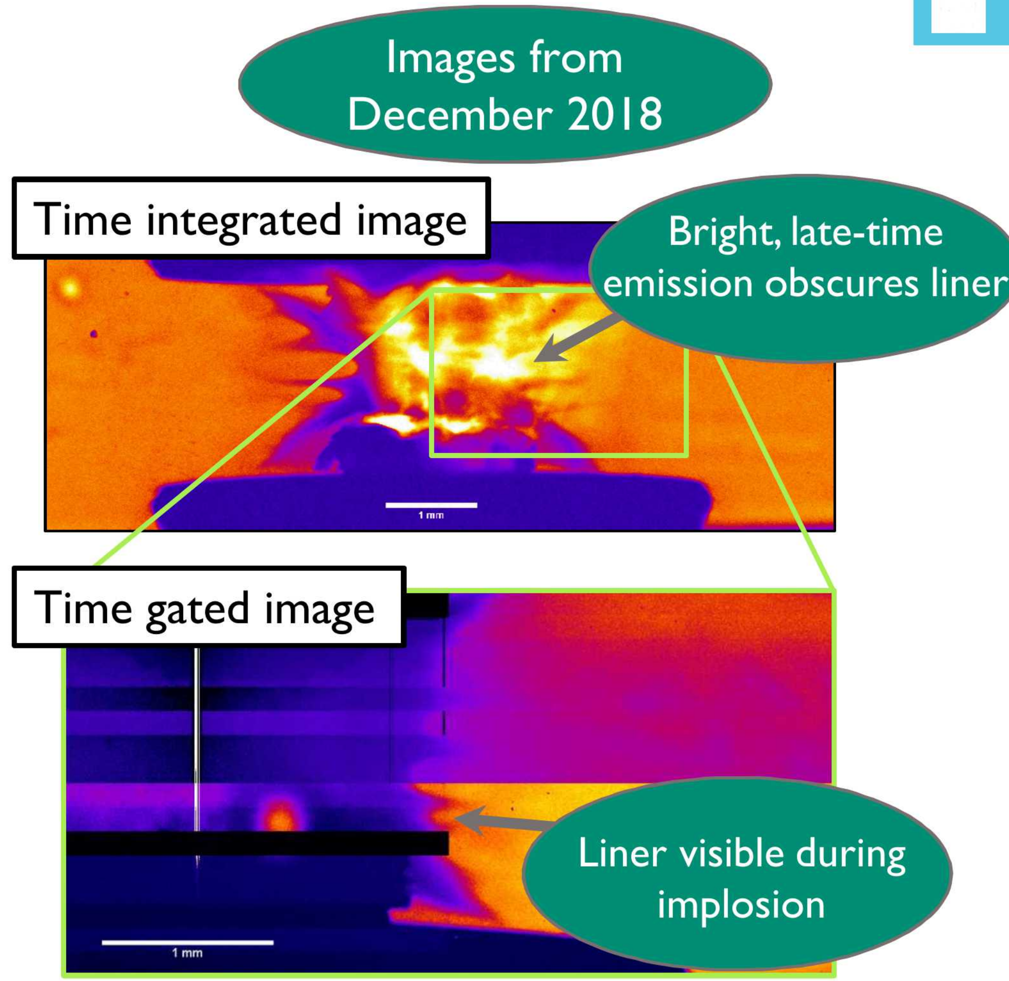


Temporal multiplexing with 2 camera systems

- Two Icarus sensors employed with multiple slits each to create a 16-frame, time-resolved set of spectra

Gated radiography is making an impact on Z experiments

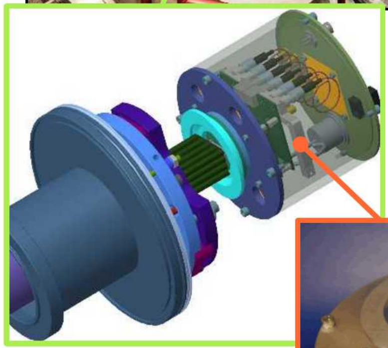


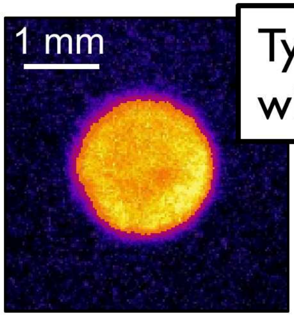


- ➢ Icarus sensor used to gate out late-time radiation, enabling higher contrast imaging of imploding liners
- ➢ Multiple frames possible on a single shot from a single line of sight
- ➢ Serious challenges in EMI, debris, shock, radiation tolerance

Time-resolved, multi-frame pinhole images are being used to diagnose laser preheat conditions

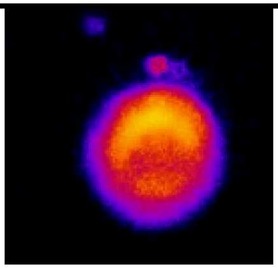
Z Final Optics Assembly

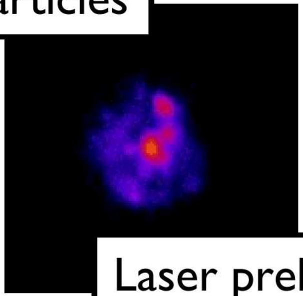




Typical laser preheat with phase plate

Laser preheat with observed dust particles

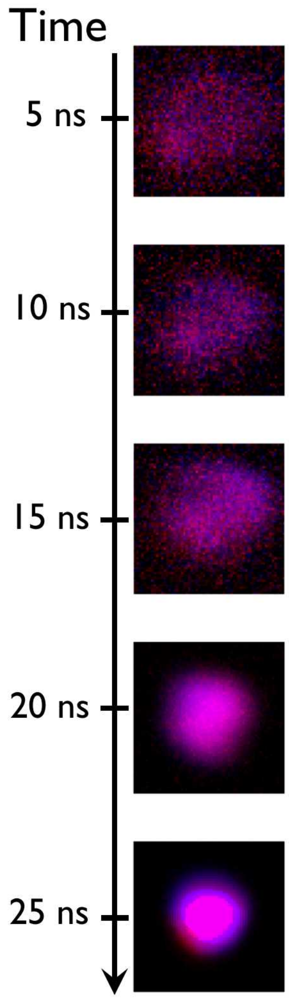




Laser preheat with no phase plate

Time series with color channels

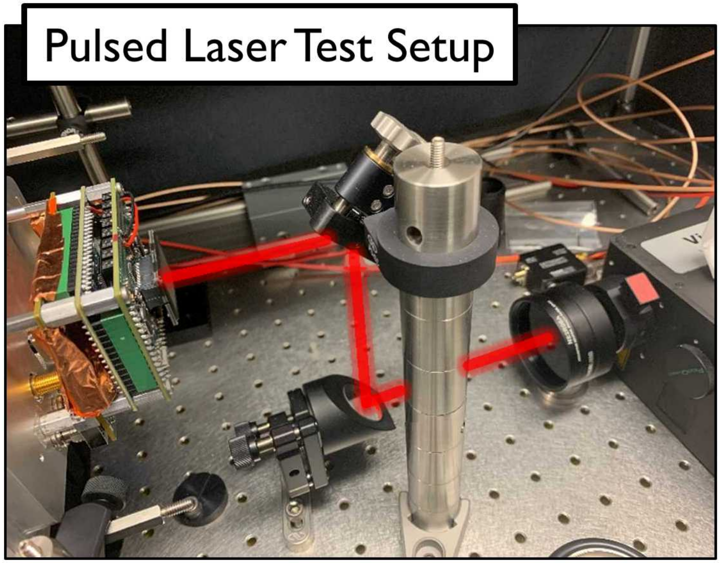
Filter 1
Filter 2

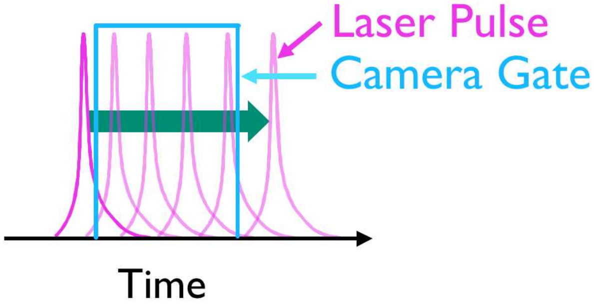


- Icarus sensor used in pinhole camera system to image MagLIF laser-induced plasma prior to stagnation
- Multiple images with two different filters

Characterization Methods

The camera's temporal gate profile is characterized by sweeping laser pulses in time



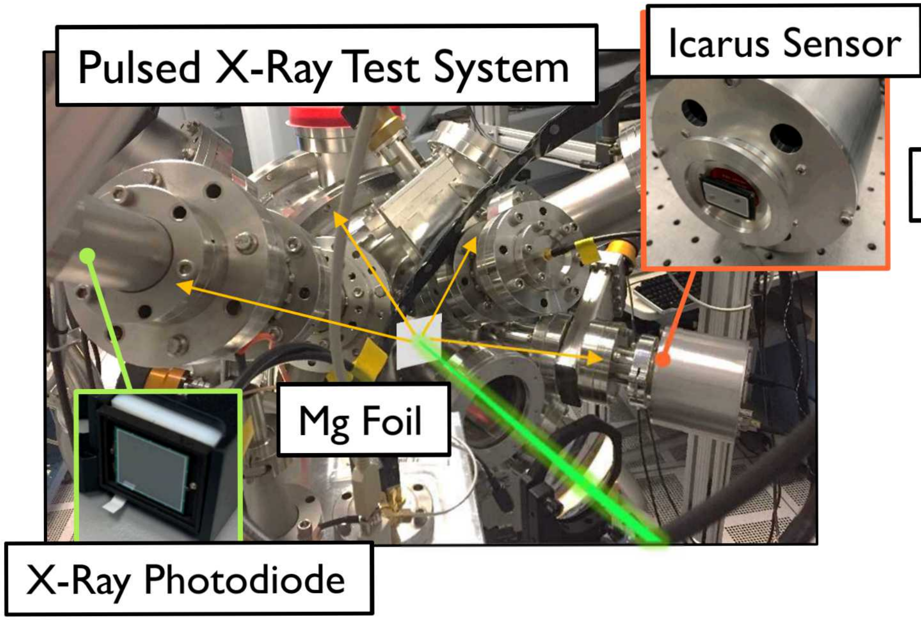


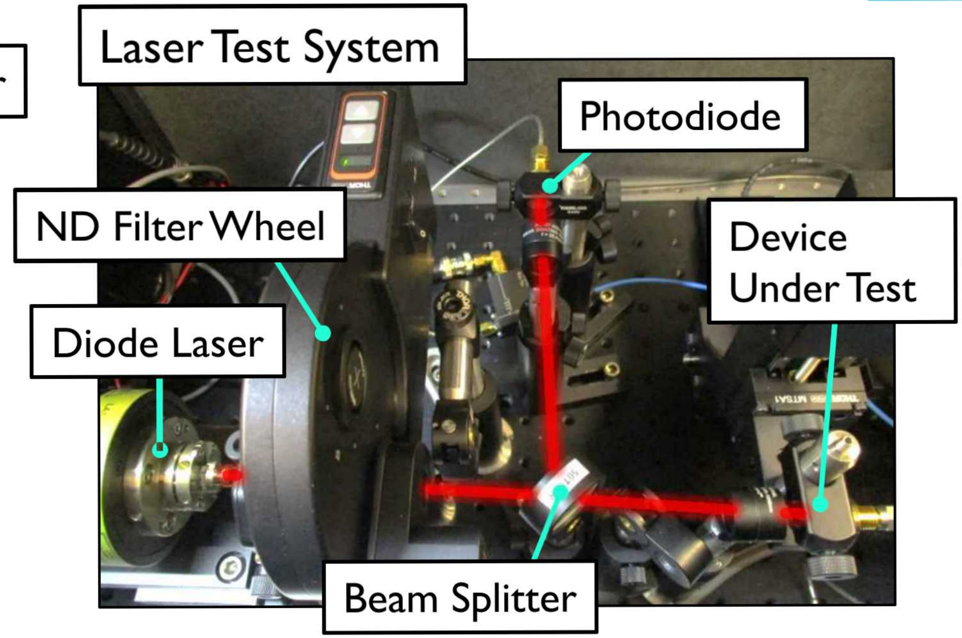
Example gate profile scan with 2 ns exposure time over 4 frames

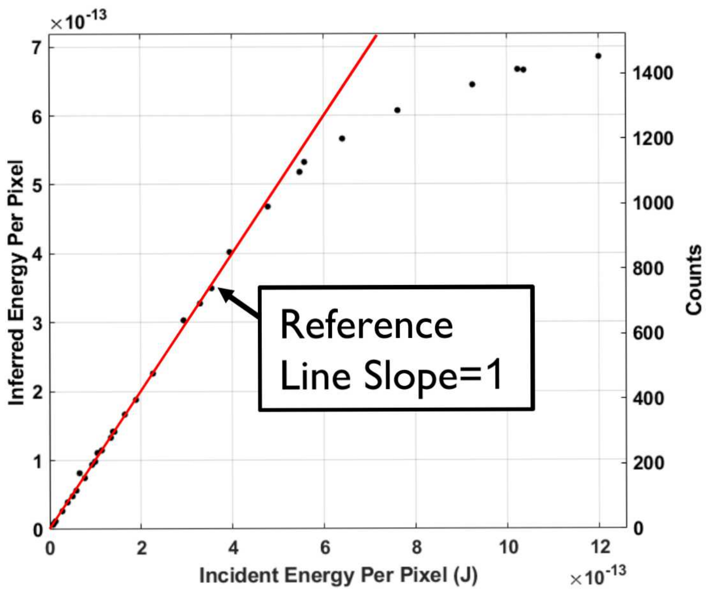
F0 F1 F2 F3

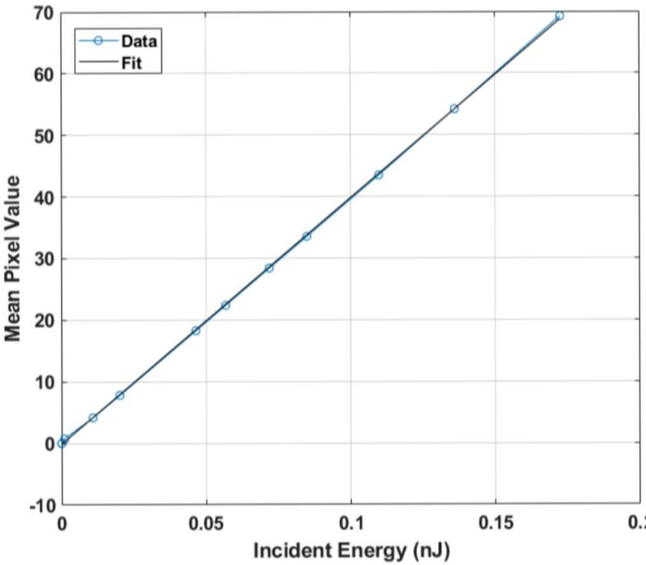
- Tabletop laser system allows rapid characterization of each sensor in a variety of timing modes

The camera's linearity and sensitivity are characterized with x-ray and laser illumination

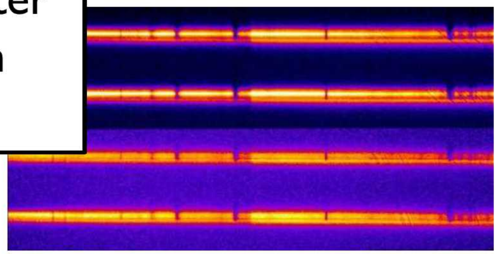


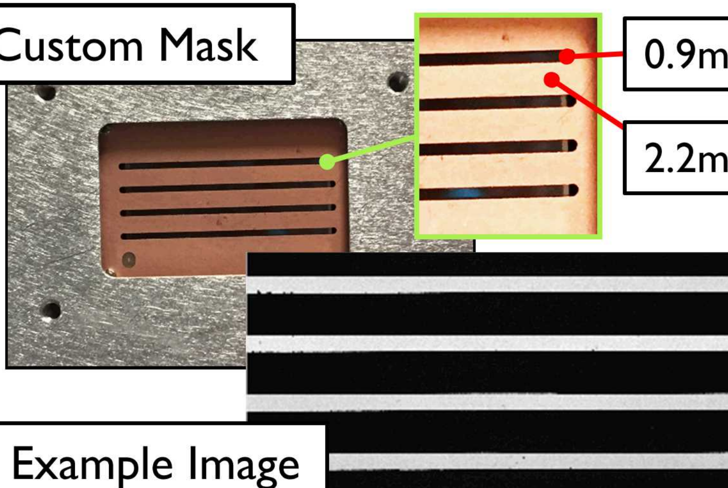


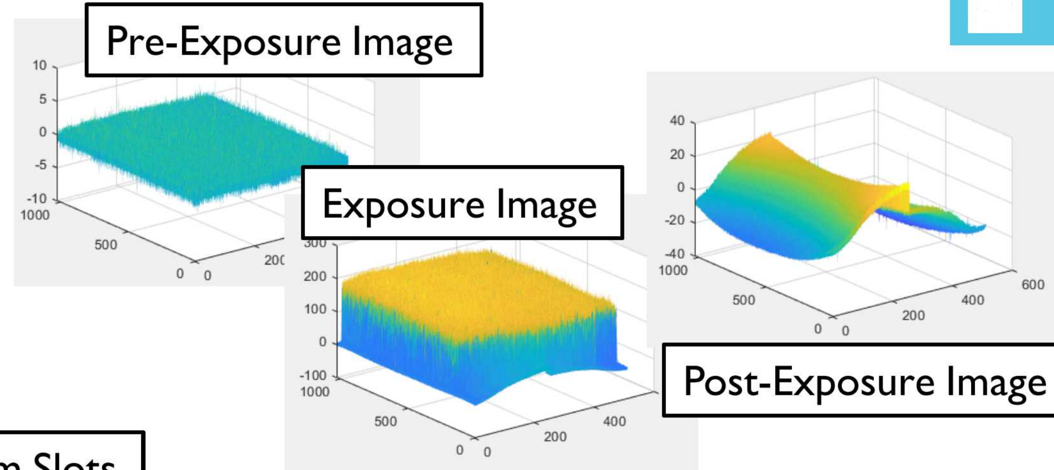


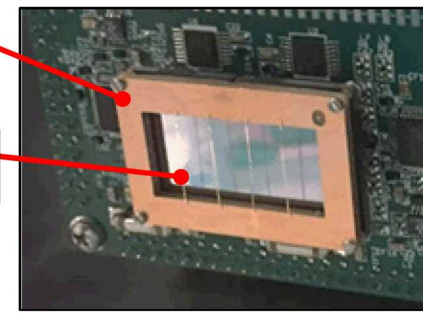


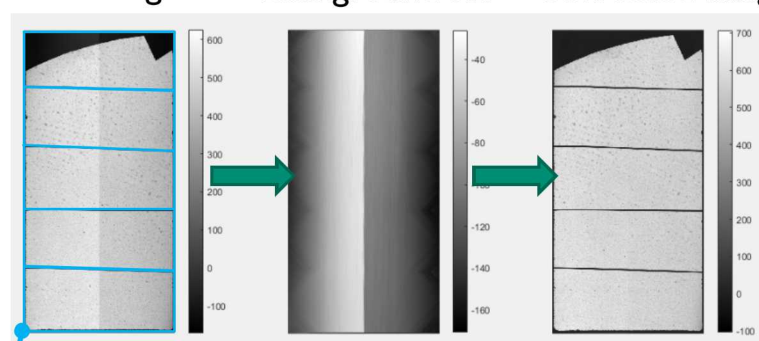
Application-specific masks aid in characterizing background











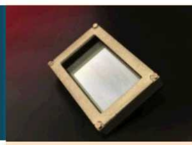
- ➢ Opacity spectrometer on Z machine utilizes 4-slit pattern, sensitive to changes in intensity along spectrum
- ➢ Custom mask mimics illumination pattern with uniform illumination to examine sensor response

Sensor Improvements

ROIC performance continues to offer improvements in speed, robustness, and timing flexibility

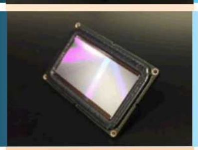
FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23
Hippogriff	Icarus V1		Icarus V2	DaedalusV1		Daedalus V2/HE		Tantalus
Delivered	*Delivered*		*Delivered*	*In Testing*				

Furi / Hippogriff



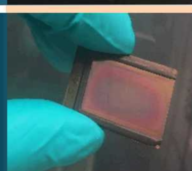
- 1st full-scale multi-frame sensors
- 1.5-2ns minimum shutter
- Optimized for 1-10 keV x-ray detection

IcarusV1/ IcarusV2



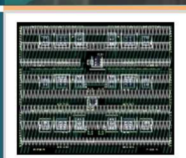
- 1st cameras compatible with pulse-dilation
- 1 ns min. shutter with 2 or 4 (Icarus-2) frames per hemisphere
- Optimized for soft x-ray, visible, and e- detection

Daedalus/ DaedalusV2&HE



- 3 frames per hemisphere (≥6 frames with interlacing)
- 1-side abutment for spectroscopy and z-pinch imaging applications
- Large well for high energy x-rays while maintaining low end sensitivity
- **Daedalus HE will use GaAs or other advanced detector**

Tantalus

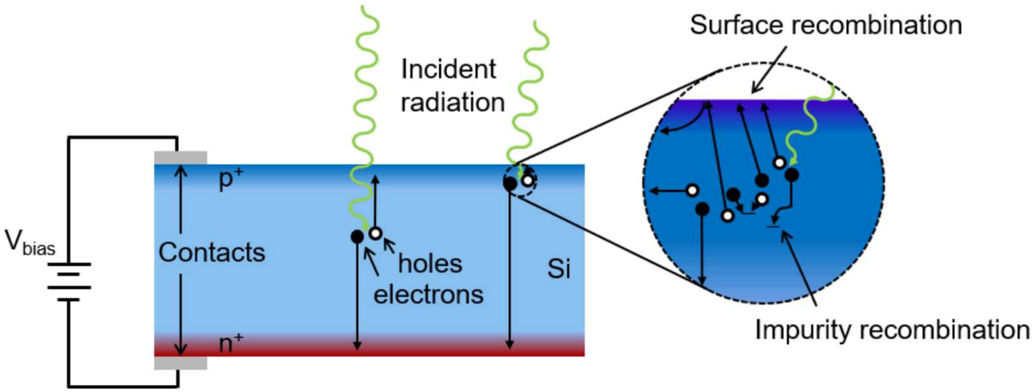


- 1st sensor in new commercial foundry process

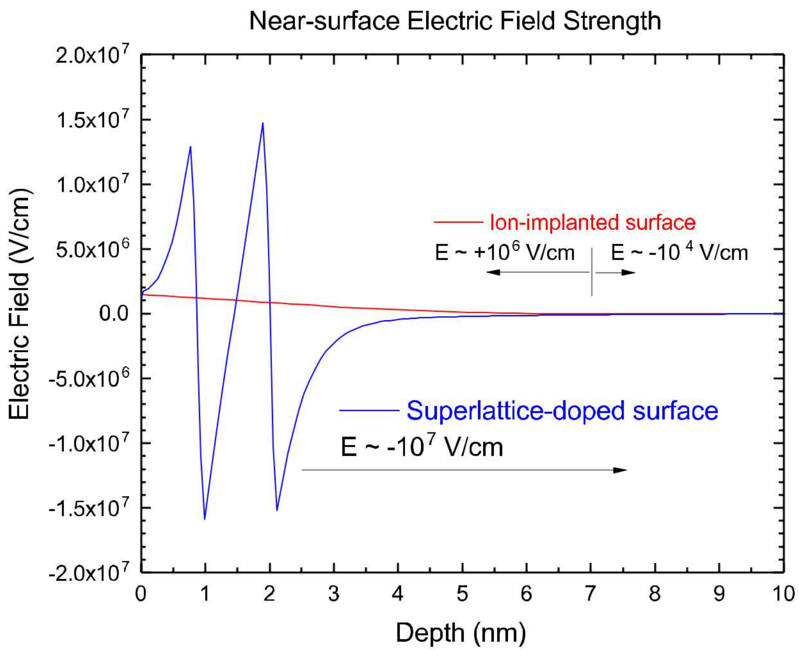
  Design goals include
  - 6 frames per pixel w/ independent quadrants (≥12 frames with interlacing)
  - 0.5 ns minimum shutter

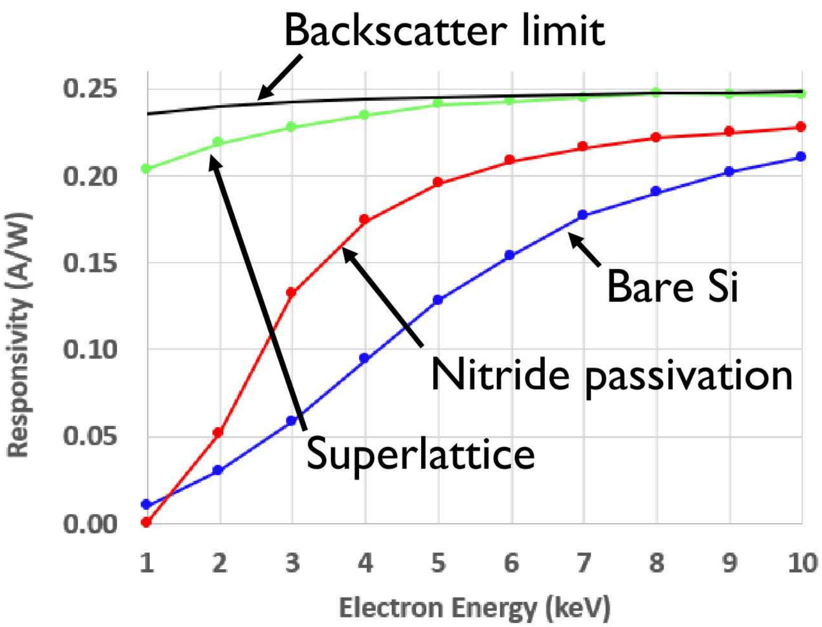
UXI Sensors

The addition of a quantum superlattice improves responsivity for shallowly absorbed particles



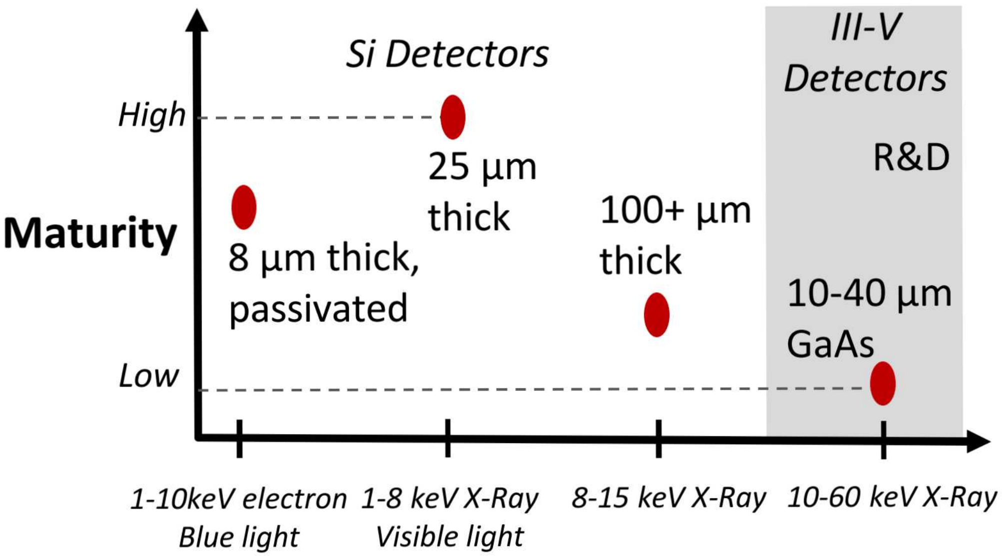
- For electrons, soft x-rays, and near-UV light, dead layer dictates detector sensitivity
- Quantum superlattice-enhanced detectors developed in partnership with NASA JPL demonstrated substantial increase in senitivity

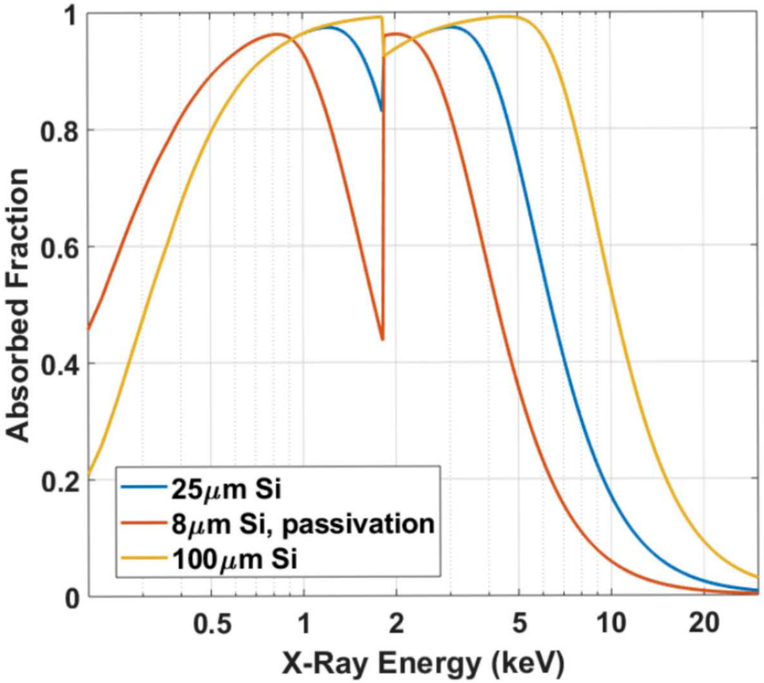




Sensor thickness can be tailored to meet application needs

- Most deployed detectors 25µm Si
  - Mature fabrication and integration
  - ~700ps impulse response
- 8µm Si deployed on a limited basis with passivation
  - Mature sensor fabrication
  - Passivation adds integration complexity
  - ~400ps impulse response
- 100µm Si being developed for greater hard x-ray sensitivity
  - Only effective up to ~15 keV x-ray energy
  - Add integration complexity
  - ~3ns impulse response

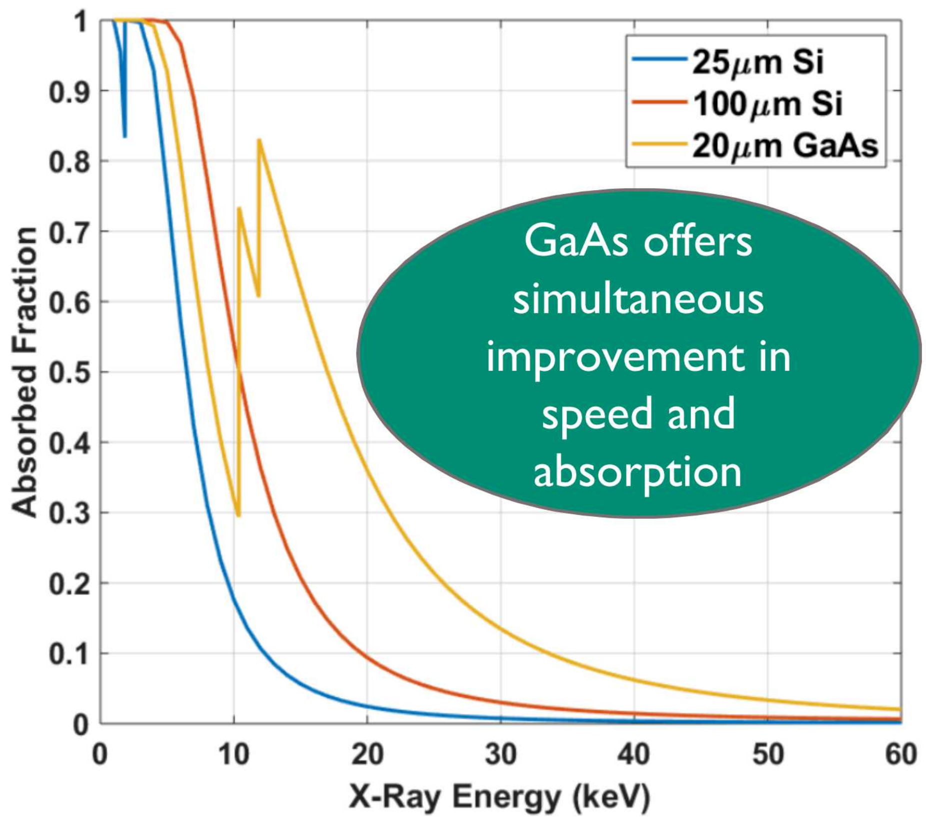


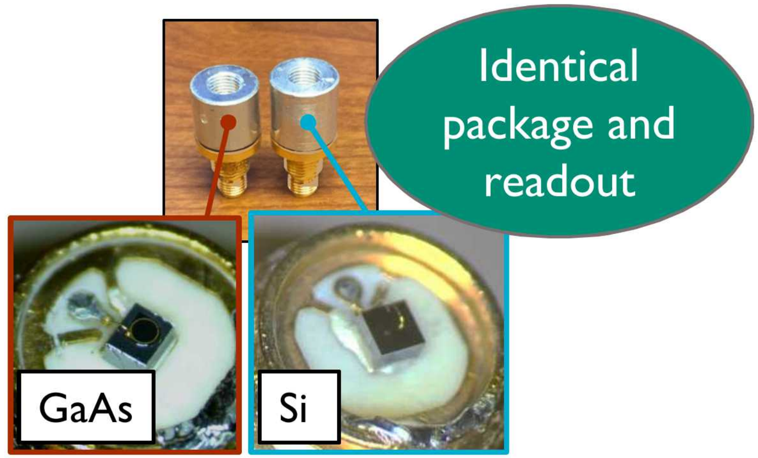


Sandia has developed fast GaAs photodiodes to improve hard x-ray sensitivity

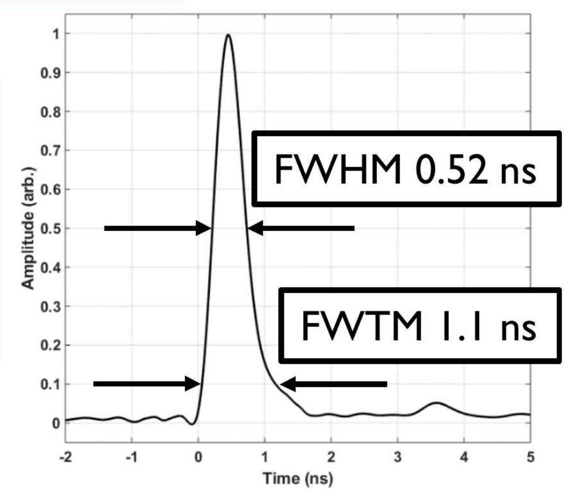
- Si hard x-ray response limited, temporal response hampered by thick detectors
- Photoelectric absorption ~Z^4

- Superior hard x-ray absorption and sub-nanosecond response demonstrated in frontside-illuminated GaAs detectors



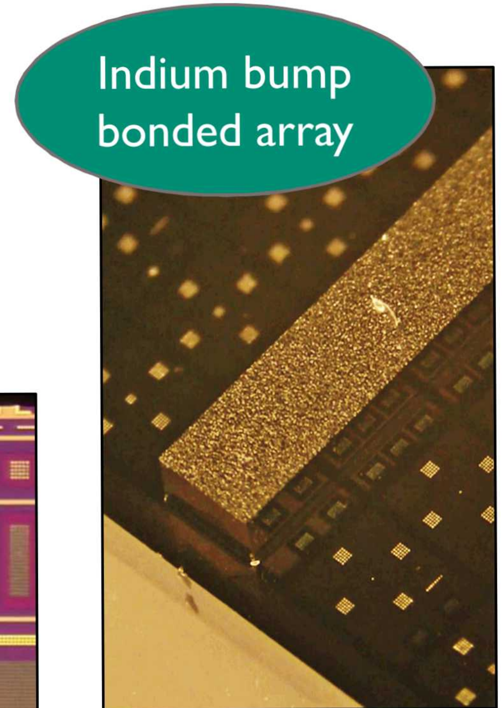


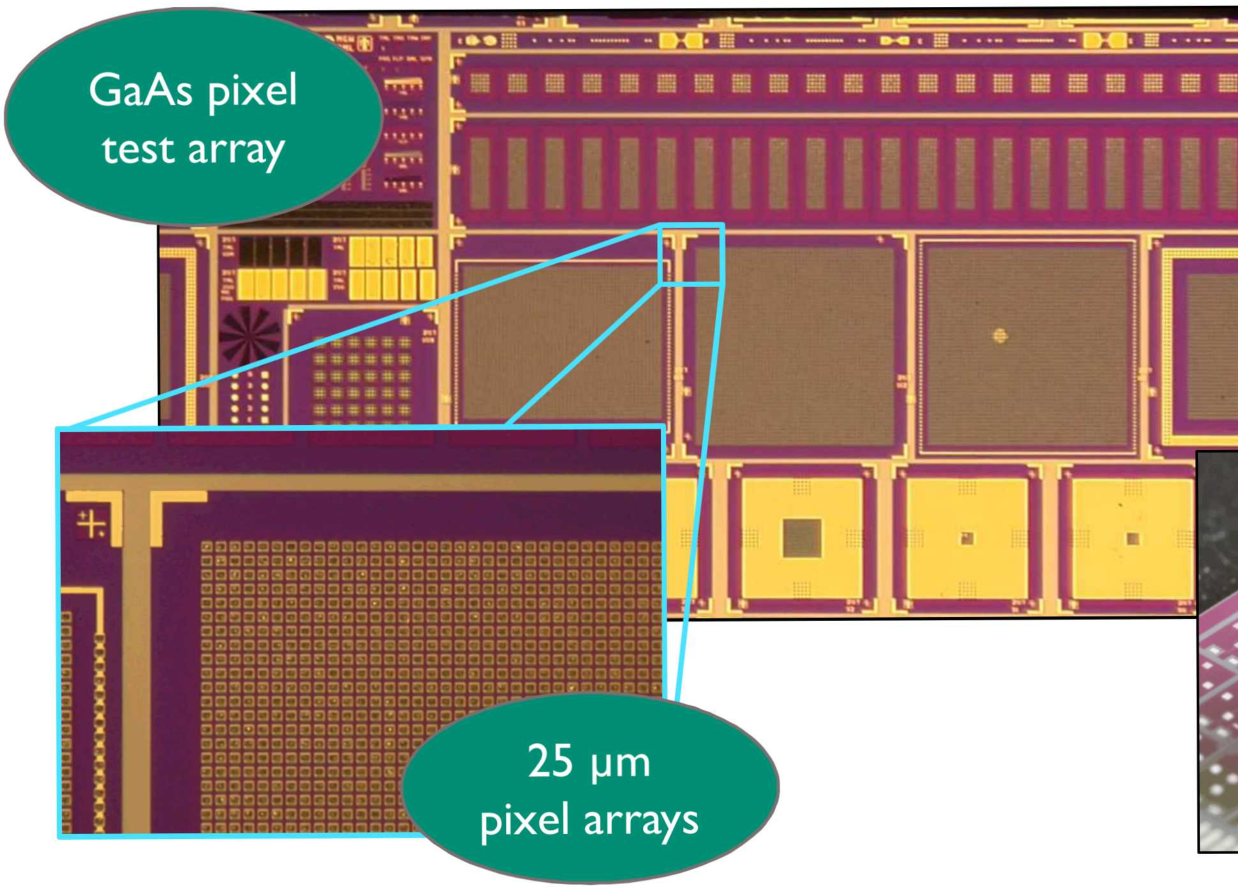
GaAs p-i-n photodiode 20 μm thick, 532 nm laser illumination

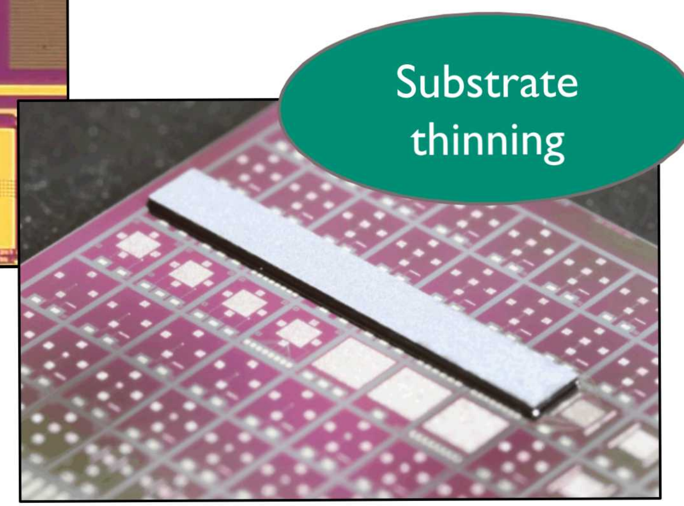


Backside-illuminated GaAs pixel arrays are being developed for hCMOS detectors

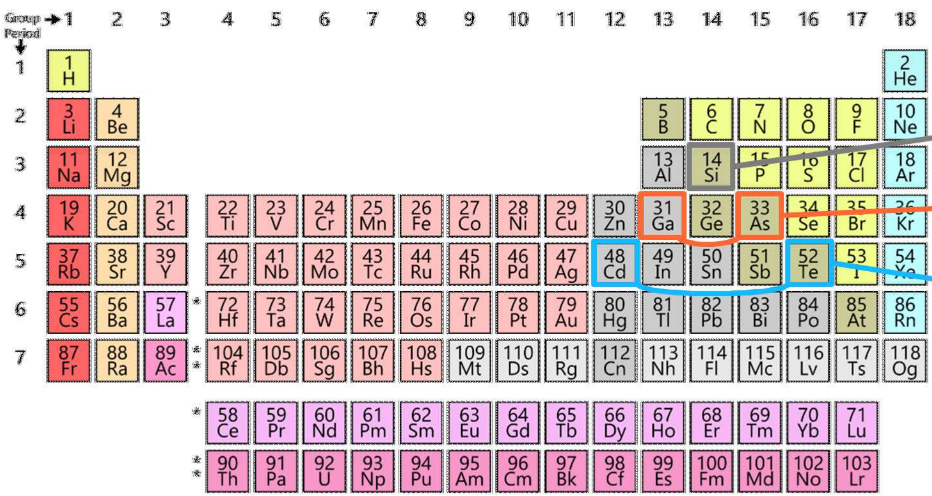
- Process changes required for hybrid CMOS compatibility
- First bonded test arrays complete
- 0.5 Mpix Icarus/Daedalus arrays available next year



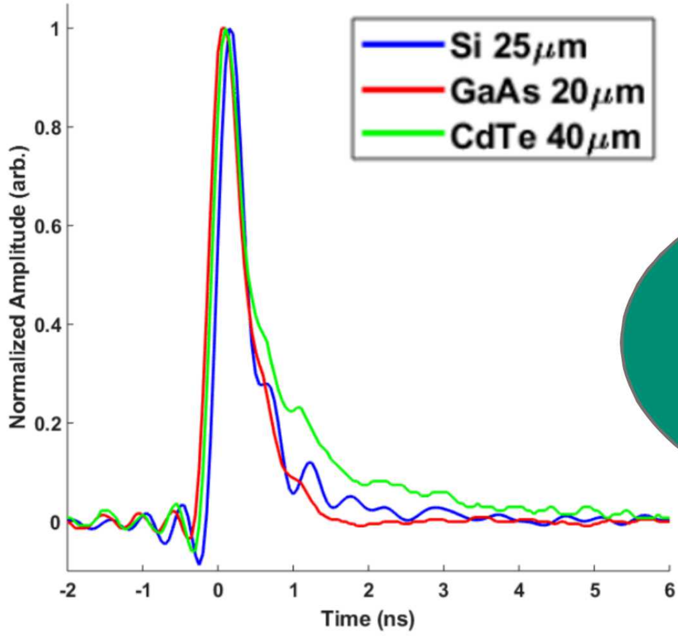




Other detector materials show promise for hard x-ray detectors



Material Investigated	Notes
Si	Mature fabrication, low Z
GaAs	Demonstrated fast detectors
CdTe	Demonstrated fast detectors
CdZnTe	Cannot obtain small detectors
GaN	Background doping too high
AlSb	Leakage current too high



Detector pulse shapes obtained with Advanced Photon Source white beam

Nanosecond-gated imagers are expanding possibilities in ICF and HED Physics

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Please see poster 3P04 for more exciting applications of UXI camera systems