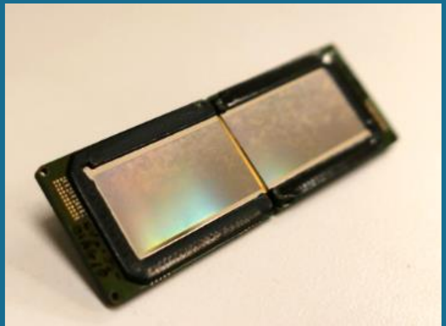
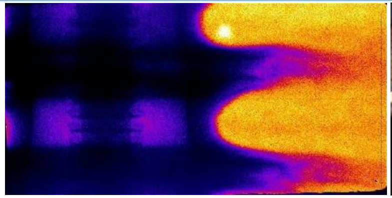
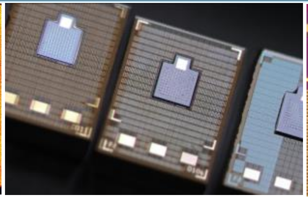
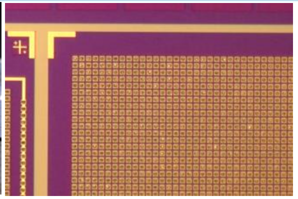
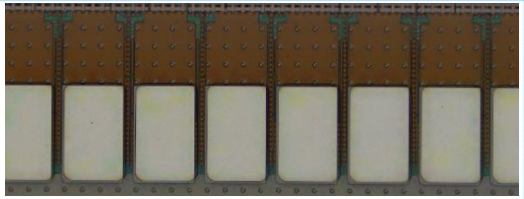
Ultrafast Imaging with the UXI Family of Hybrid CMOS Detectors



Quinn Looker

Sandia National Laboratories
Albuquerque, NM

International Forum on Detectors for Photon Science (IFDEPS)
Brookhaven National Laboratory
March 17-20, 2024

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SAND2024-03049PE

The UXI Program is a Multi-Organizational Effort

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Brad Golick
Robin Benedetti
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Nathan Palmer

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NALU SCIENTIFIC

Isar Mostafanezhad
Ryan Pang

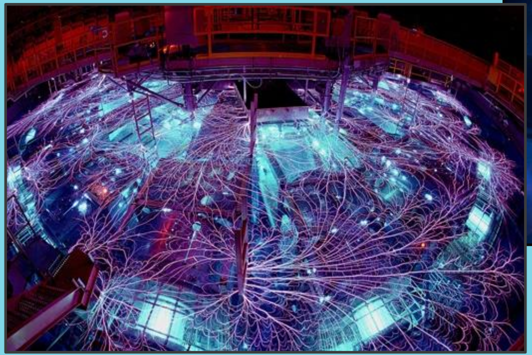
John Stahoviak
Aaron Lee

NHanced Semiconductors, Inc.

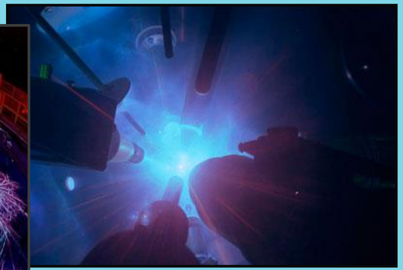
INTEGRA TECHNOLOGIES
An Employee Owned Company

Sandia's Hybrid CMOS Detectors were Developed for Inertial Confinement Fusion and High Energy Density Physics Applications

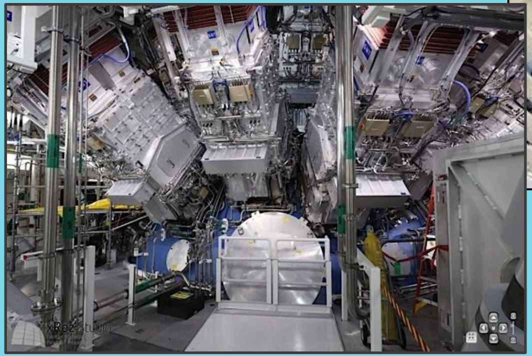
National Inertial Confinement Fusion Facilities



Sandia Z Machine



OMEGA LLE



Livermore NIF

CEA LMJ

- High Intensity (~MJ x-rays, 10^{17} neutrons in ~ns)
- Low Shot Rate (<5 shots/day)

Light & Particle Sources

SLAC LCLS

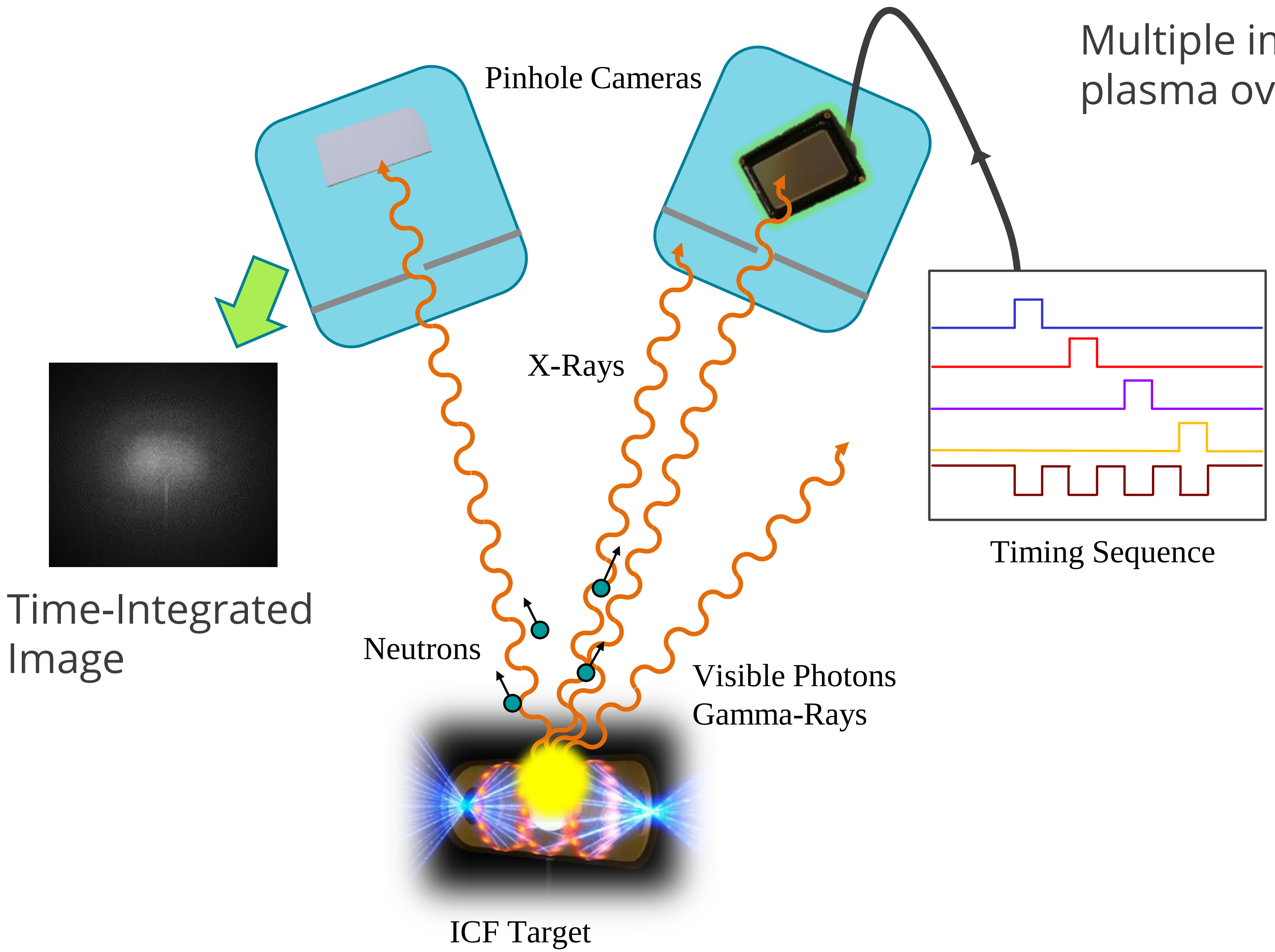
Sandia ZBL

ANL APS

LLNL JLF

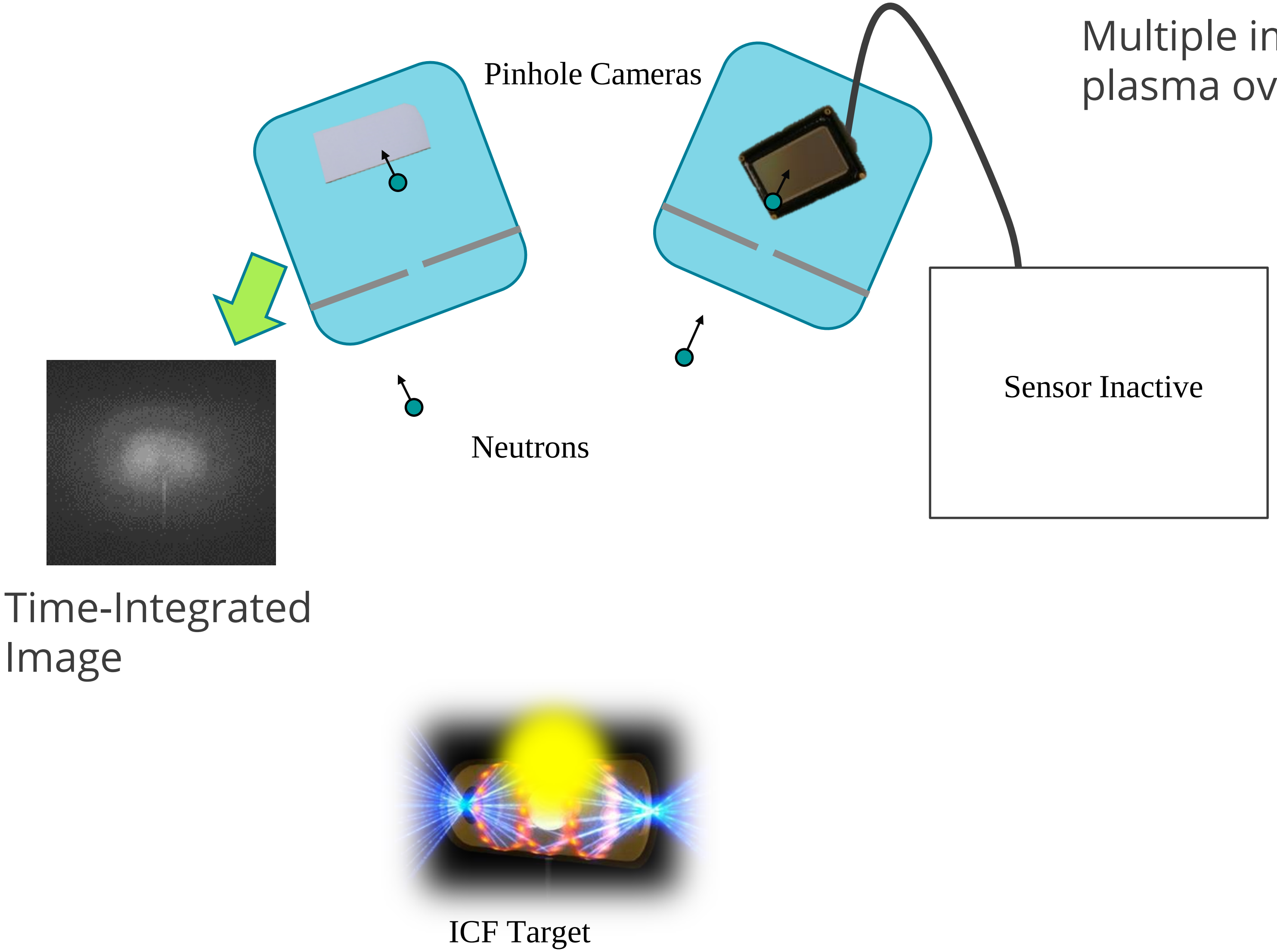
- Early work adapting to light sources
- Higher rep rate, lower intensity

Burst-Mode Imaging Used for Rapidly Evolving Plasmas



Multiple image acquisitions of plasma over ~ns time scales

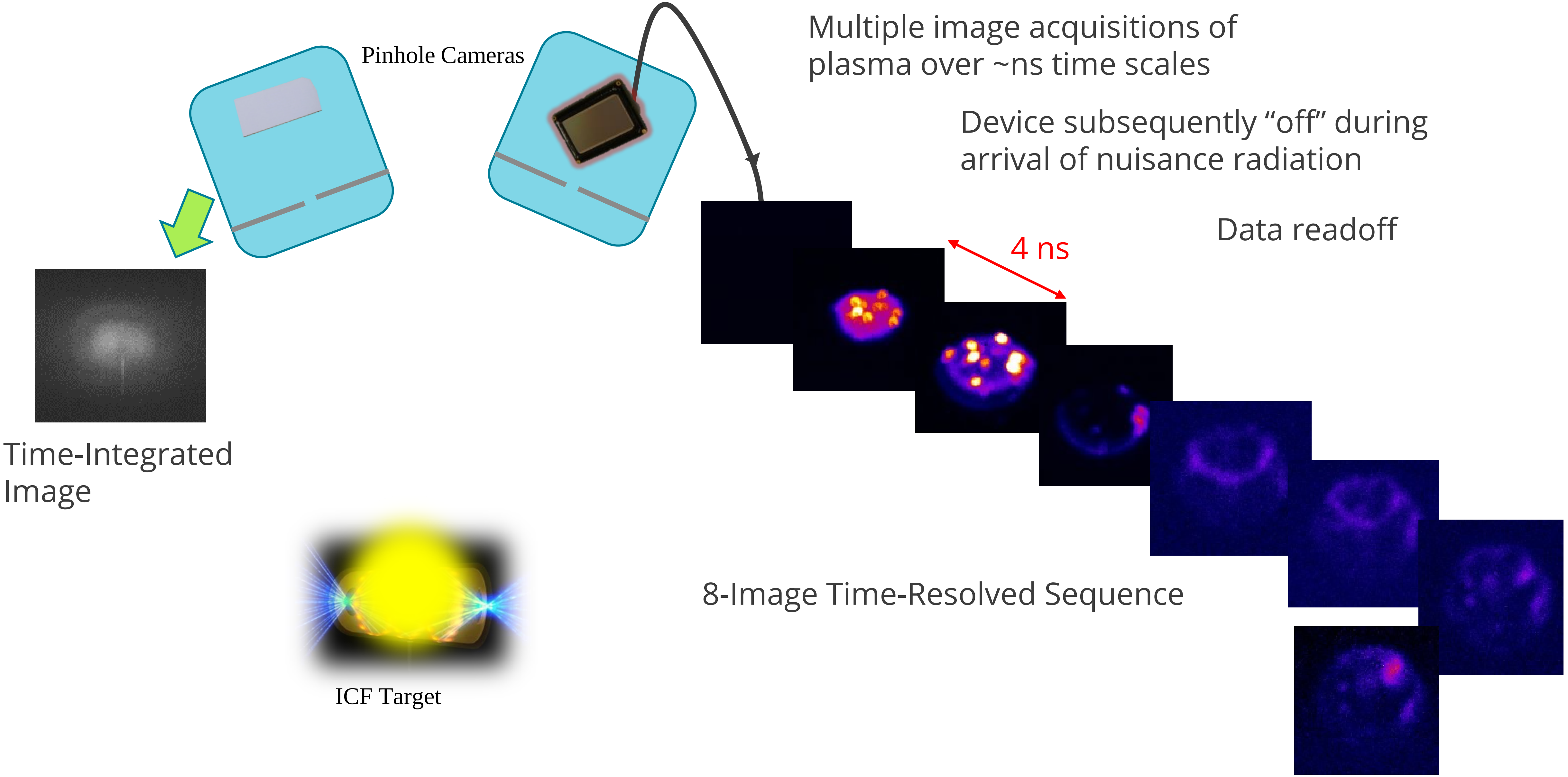
Burst-Mode Imaging Used for Rapidly Evolving Plasmas



Multiple image acquisitions of plasma over ~ns time scales

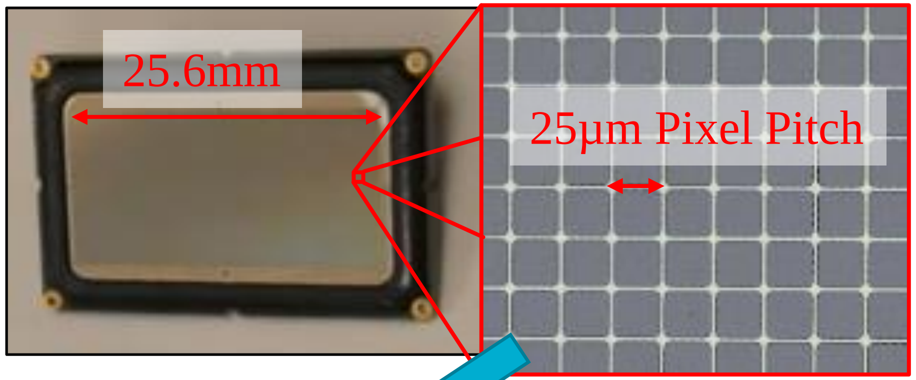
Device subsequently “off” during arrival of nuisance radiation

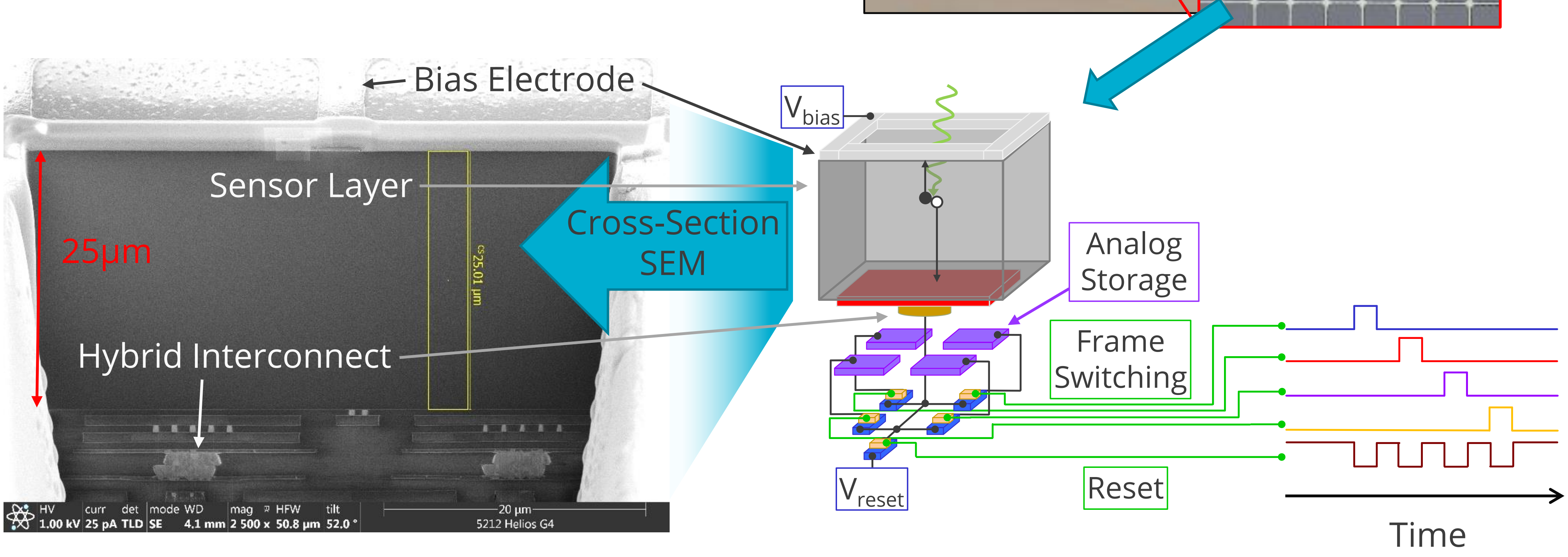
Burst-Mode Imaging Used for Rapidly Evolving Plasmas



Hybrid CMOS Detectors Enable Multiple, Time-Resolved Images Along a Single Line-Of-Sight

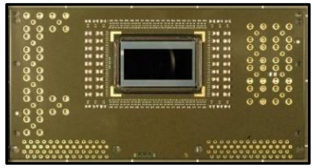
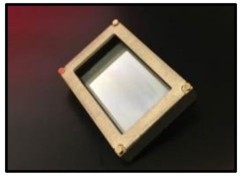
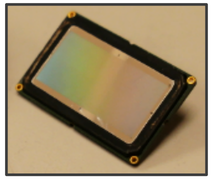
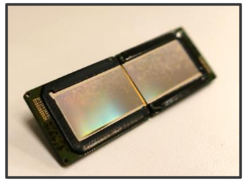
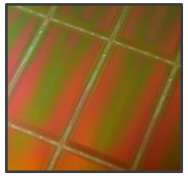
- Direct detection in semiconductor sensor
- High Soft X-ray Quantum Efficiency (50% for 6 keV)
- 100% fill factor within 3.2 cm^2 area
- Multiple frames on identical line-of-sight
- Digital image readout



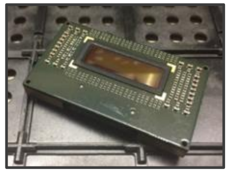
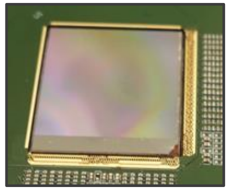
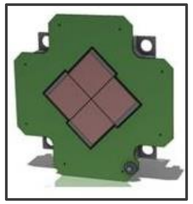


The Sandia hCMOS Family has Two Branches

	Retired		Deployed	Prototype	In Production
	Furi	**Hippogriff**	**Icarus V1/V2**	**Daedalus V1/V2**	**Tantalus**
Min. Integration time	~1.5 ns	~2 ns	~1.5 ns	~1.0 ns	~0.5 ns
Frames	2	2 [a]	4 [b]	3 [a,b]	4 [a,c]
Pixels	448 × 1024	448 × 1024	512 × 1024	512 × 1024	512 × 1024
Capacitor Full Well	1.5 million e^-	1.5 million e^-	0.7 million e^-	1.5 million e^-	0.5 million e^-

	Retired	Prototype	In Production
	Proteus	**Kraken V1**	**Kraken V2**
Min. Integration time	50 ns	50 ns	50 ns
Frames	4 [d]	4 [d]	8
Pixels	256 × 768	800 × 800	800 × 800
Capacitor Full Well	0.4 million e^-	0.4 million e^-	0.4 million e^-

[a] Row interlacing option for 2x, 4x, or more frames
[b] Left/right half independent timing
[c] Quadrant independent timing
[d] Doubled when CDS inactive

A review of Sandia's Ultrafast X-Ray Imager Program:
J. L. Porter et al., *Rev. Sci. Instr.* Vol. 94, p. 061101 (2023)

The Sandia UXI Family Comprises Nanosecond Gated Sensors

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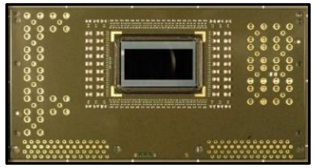
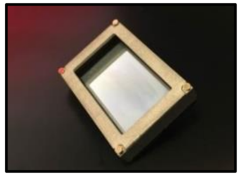
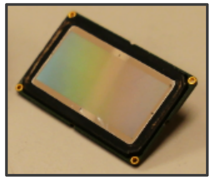
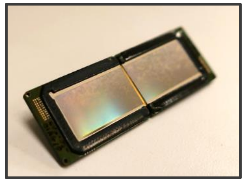
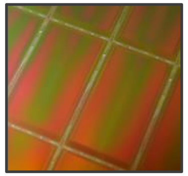
Tiling Option	No	No	No	One Side	No
CMOS Process	350 nm (SNL)	350 nm (SNL)	350 nm (SNL)	350 nm (SNL)	130 nm (Tower Jazz)
Pixels	448 × 1024	448 × 1024	512 × 1024	512 × 1024	512 × 1024
Pixel Size	25 μm × 25 μm	25 μm × 25 μm	25 μm × 25 μm	25 μm × 25 μm	25 μm × 25 μm
Capacitor Full Well	1.5 million e^-	1.5 million e^-	0.7 million e^-	1.5 million e^-	0.5 million e^-

A review of Sandia's Ultrafast X-Ray Imager Program:
J. L. Porter et al., *Rev. Sci. Instr.* Vol. 94, p. 061101 (2023)

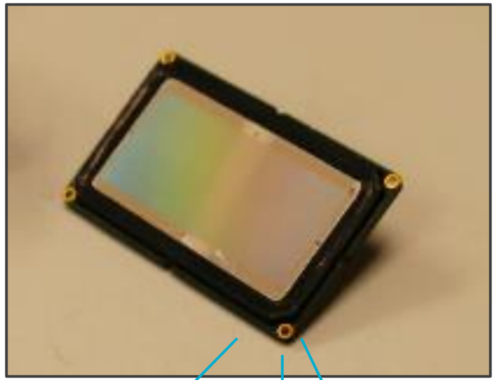
Icarus is the First Widely Deployed Detector of the SNL hCMOS Family

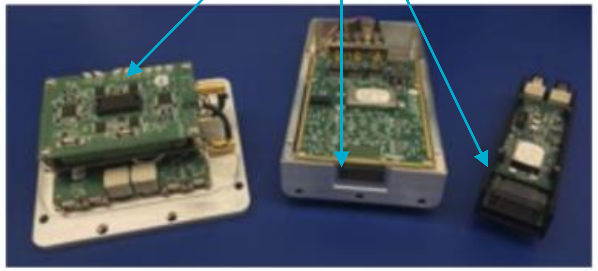
- First true half Megapixel array of the line
- 4 frames per pixel
- Higher gain optimized for smaller signals
- Small package constructed using standard techniques

	Icarus
Tech. Node	SNL 350nm
# Pixels	1024 x 512
Pixel Size	25μm x 25μm
# Frames	4 [a]
Full well	700ke$^-$
Min. gate time	~1.5ns
Abutment	No

[a] 8 frames possible when using independent sensor half timing

Icarus Detector Module





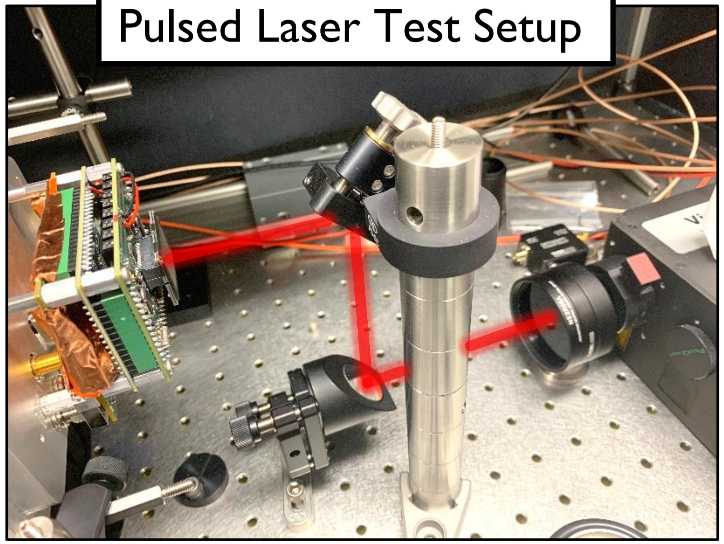
Supporting Electronics Variants

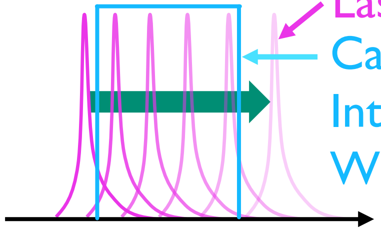
L. Claus et al., *Proc. SPIE* 103900A (2017)

Routine Optical Characterization Demonstrates Multi-Frame Integration Capability

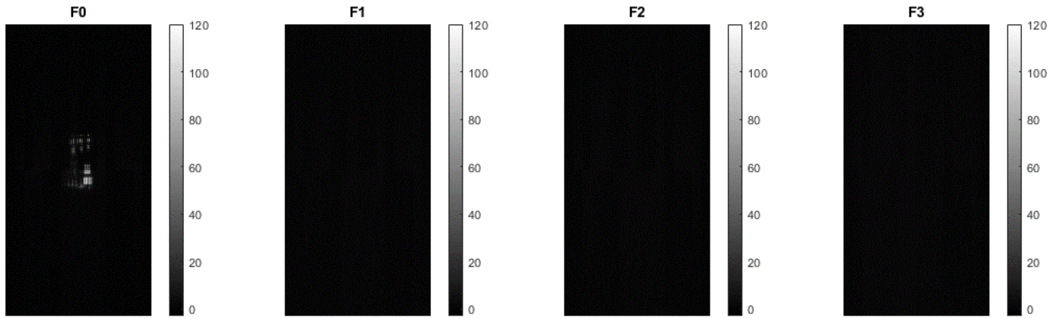
- Direct pulsed laser illumination of sensor
- Vary relative delay of camera and laser

Pulsed Laser Test Setup

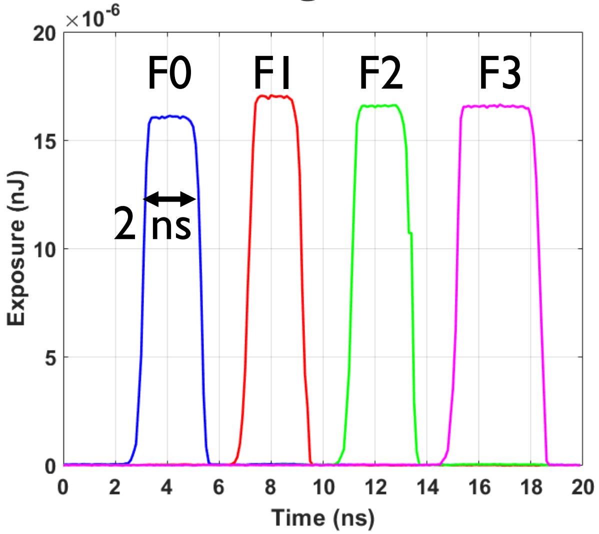




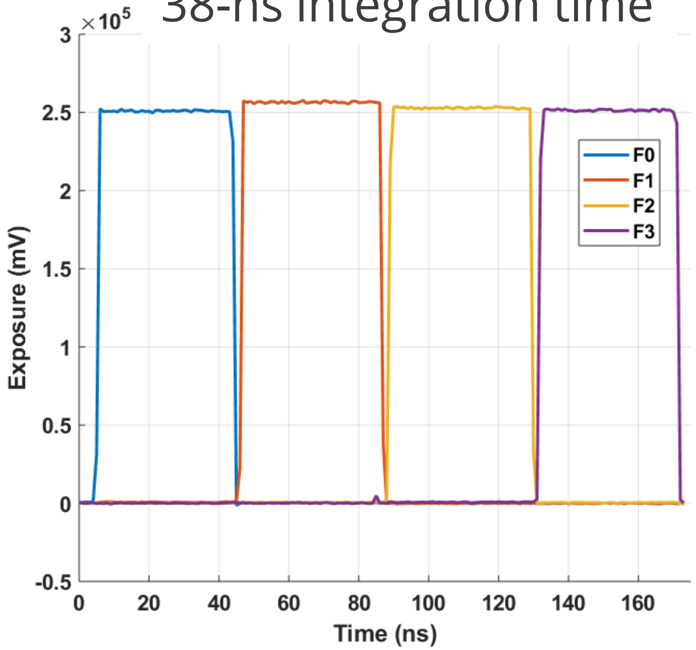
Example Image Set



2-ns integration time



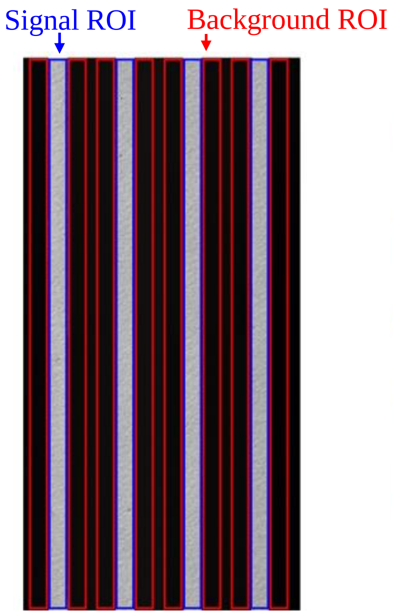
38-ns integration time



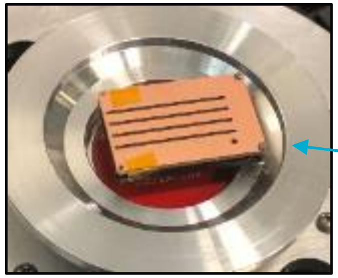
Pulsed X-Ray Characterization Demonstrates Linearity and Saturation Behavior

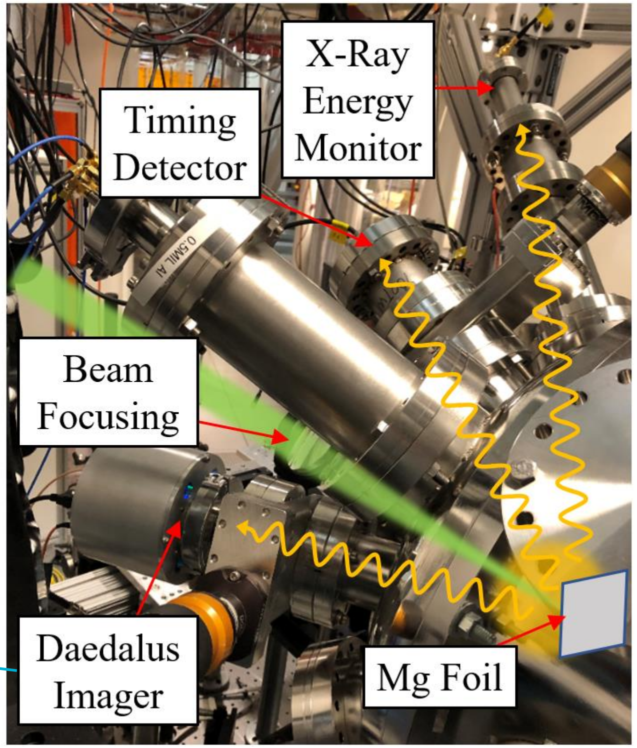
- Laser-induced plasma x-ray source ~1ns duration
- Intensity measured by x-ray photodiodes
- Imager response in linear region and saturation

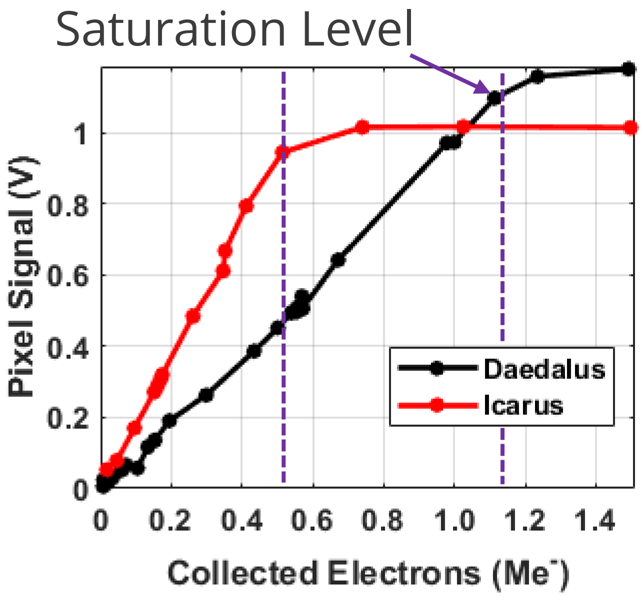
Example Image



Slit Mask



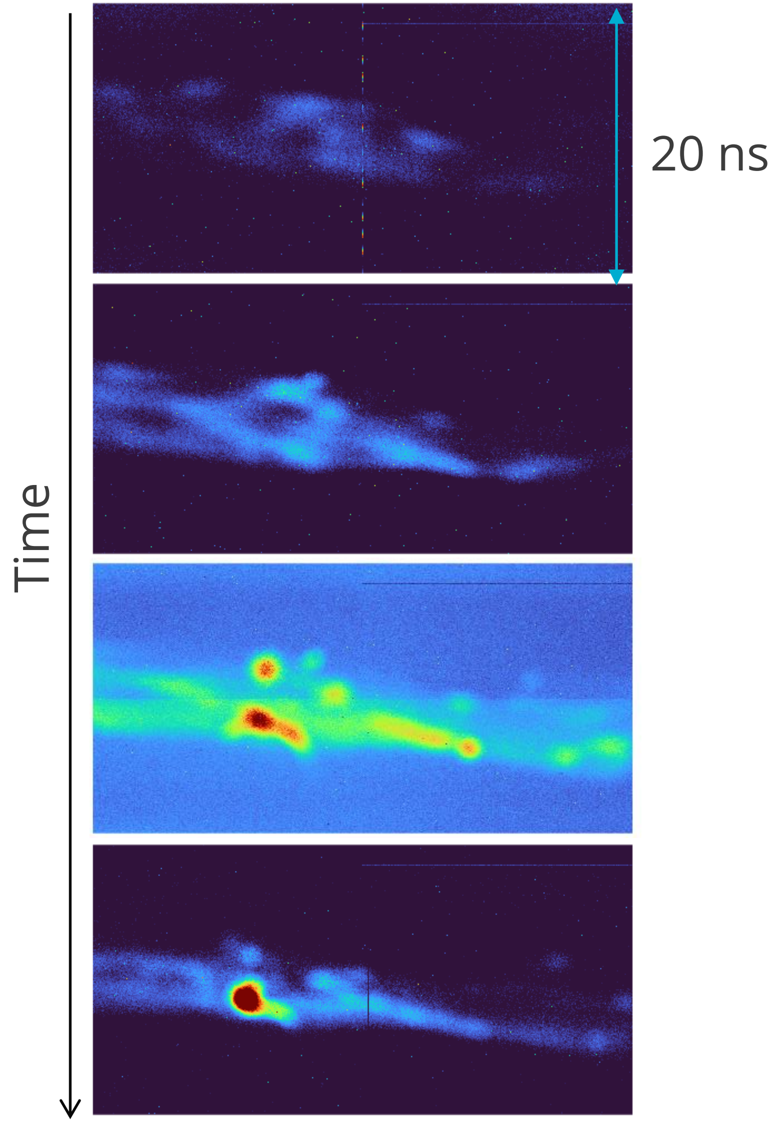




Looker et al., *RSI* 91 043502 (2020)
Looker et al., *RSI* 94 113505 (2023)

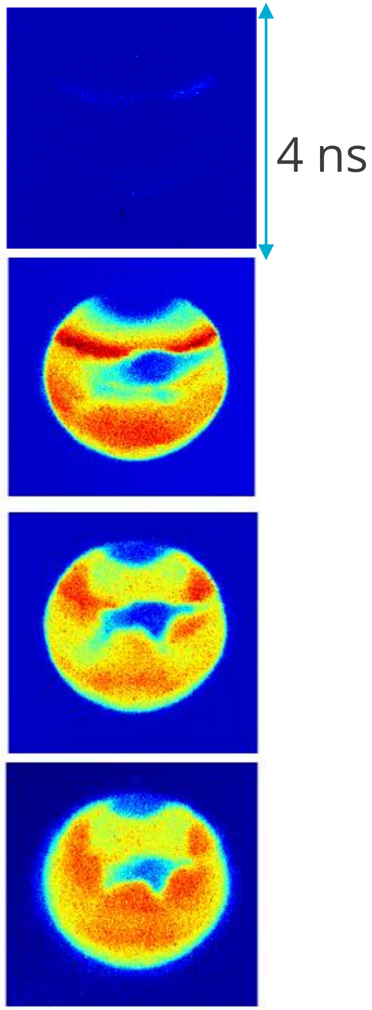
Icarus Enables Time-Resolved Imaging of Hot Plasmas

Evolution of magnetic reconnection layer on Z



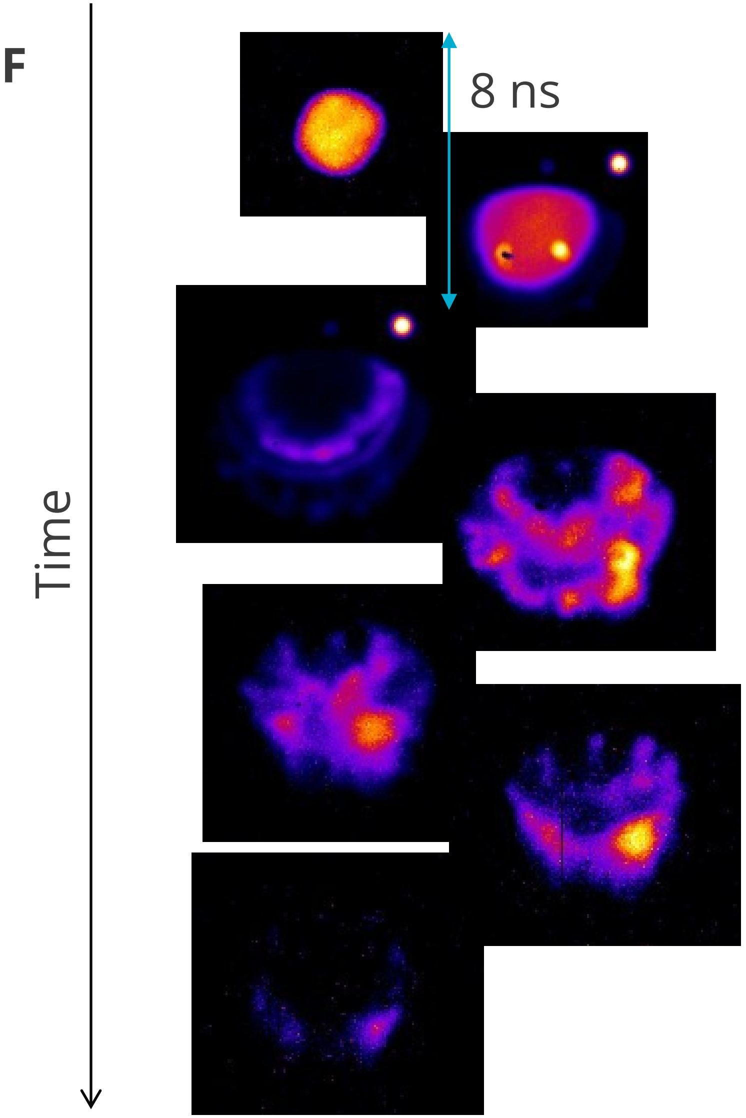
R. Datta et al., *PRL* in review

Gated LEH Images on NIF



H. Chen et al., *RSI.* 87 11e203 (2016)

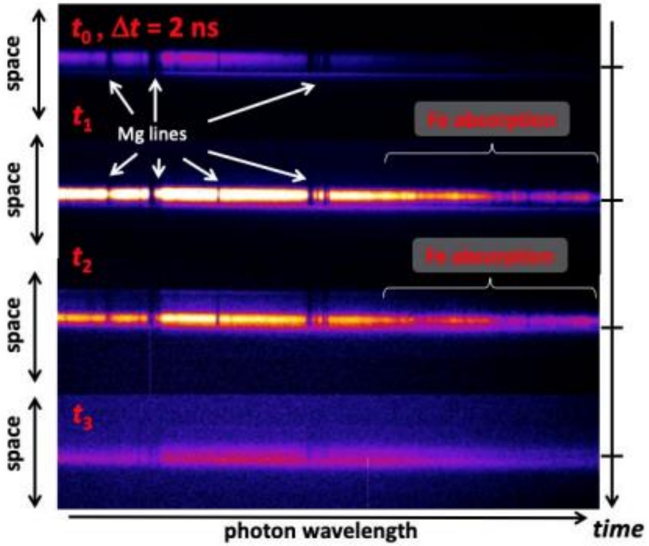
Laser Entrance Window of MagLIF Target

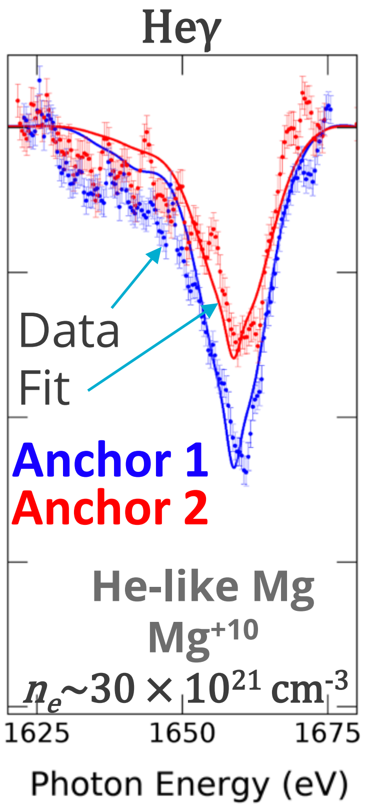


Icarus Enables Time-Resolved Spectroscopy

Opacity Platform

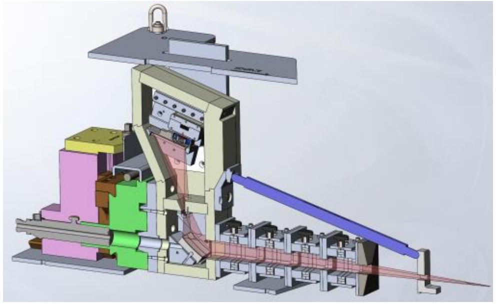
Adding time resolution to quantitative opacity measurements on Z and NIF

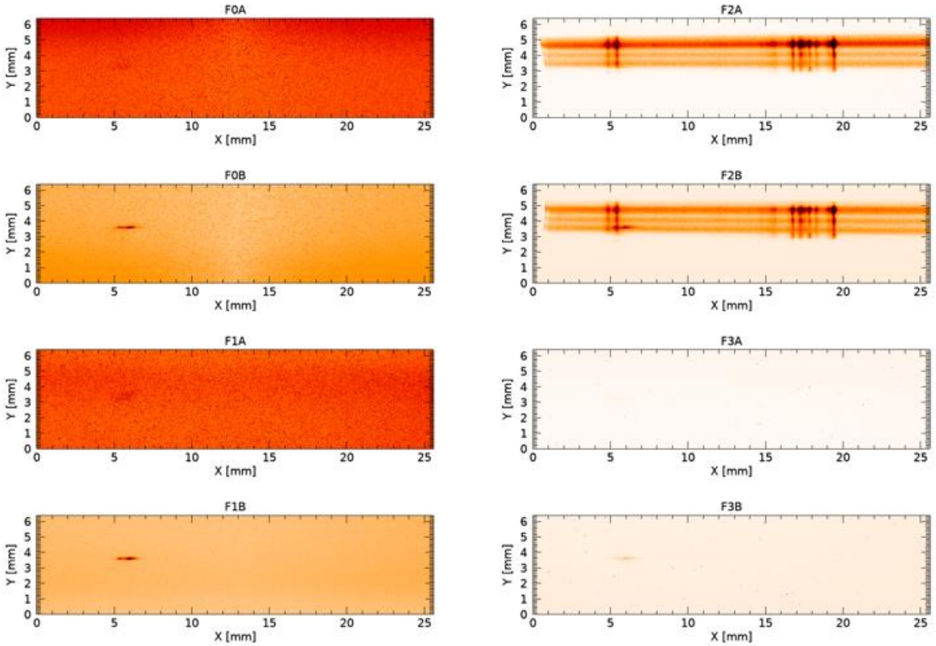




MONSSTR

Time-resolved spectrometer for hot plasmas on Z

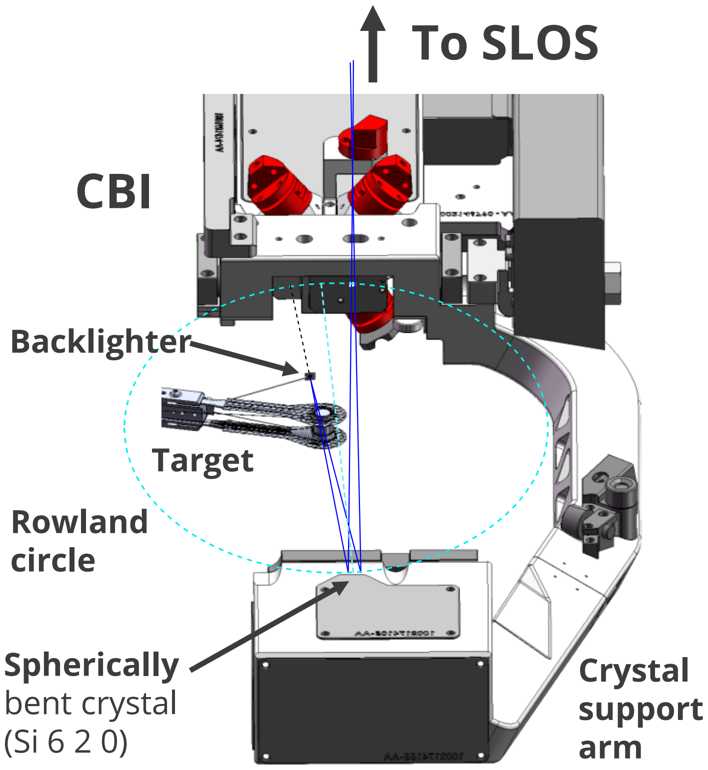


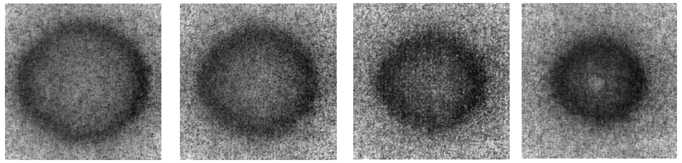


Icarus Enables Multi-Frame Gated Backlighting

CBI-SLOS on NIF

Time-resolved mix measurement in imploding capsules

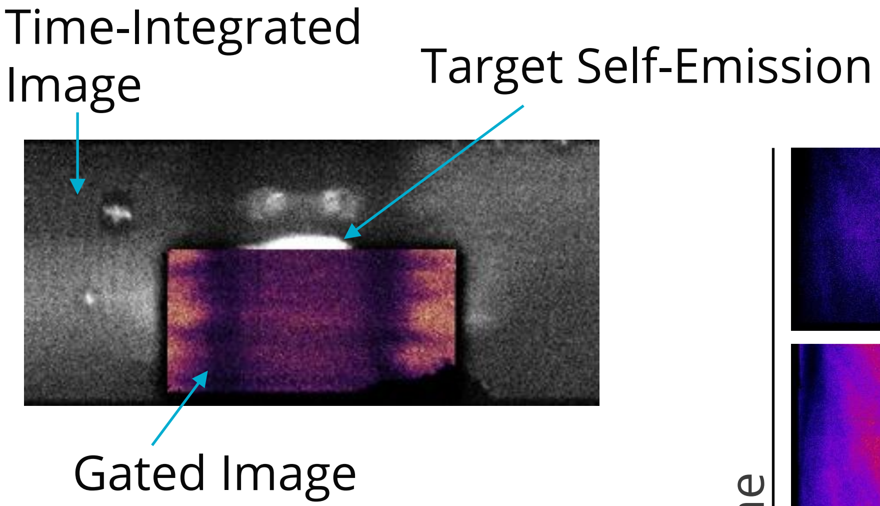




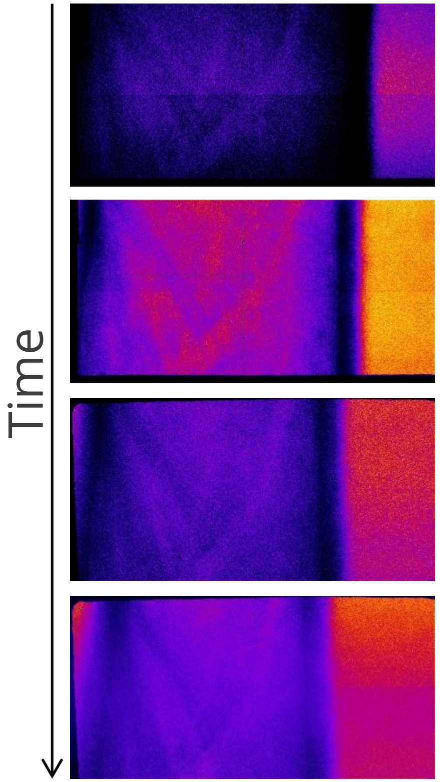
Hall et al., *RSI* 90 013702 (2019)

Gated Backlighting on Z

A single gated image avoids target self-emission...

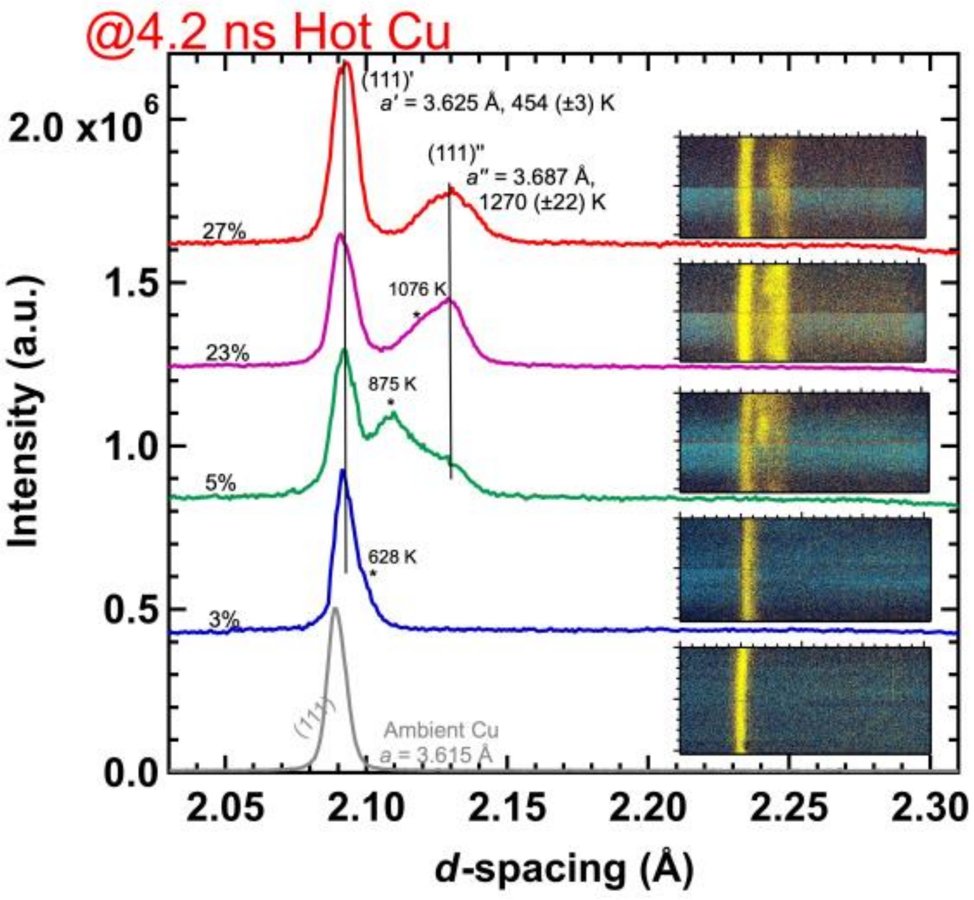


And newly developed multi-frame backlighting provides multiple measurements *on the same shot*.



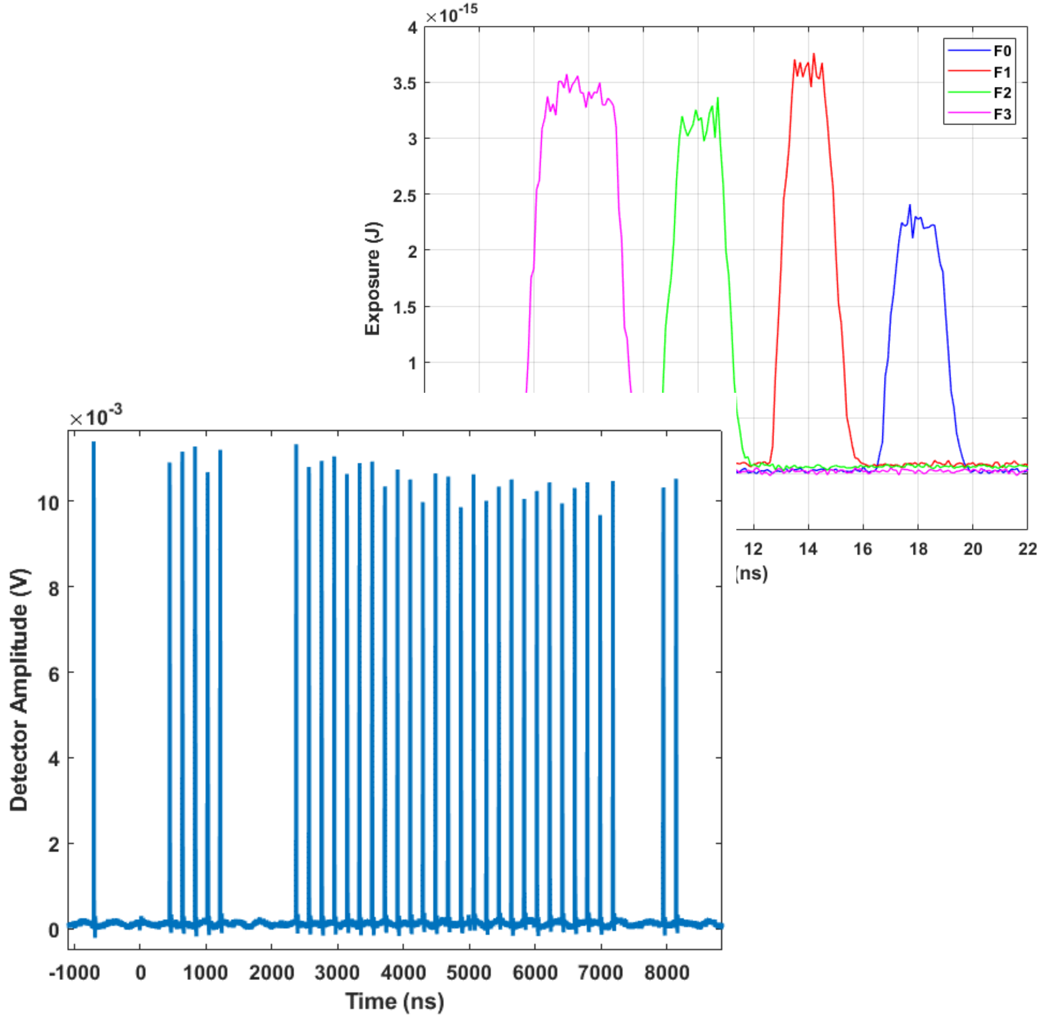
Initial Demonstration of Icarus Performance at Light Sources

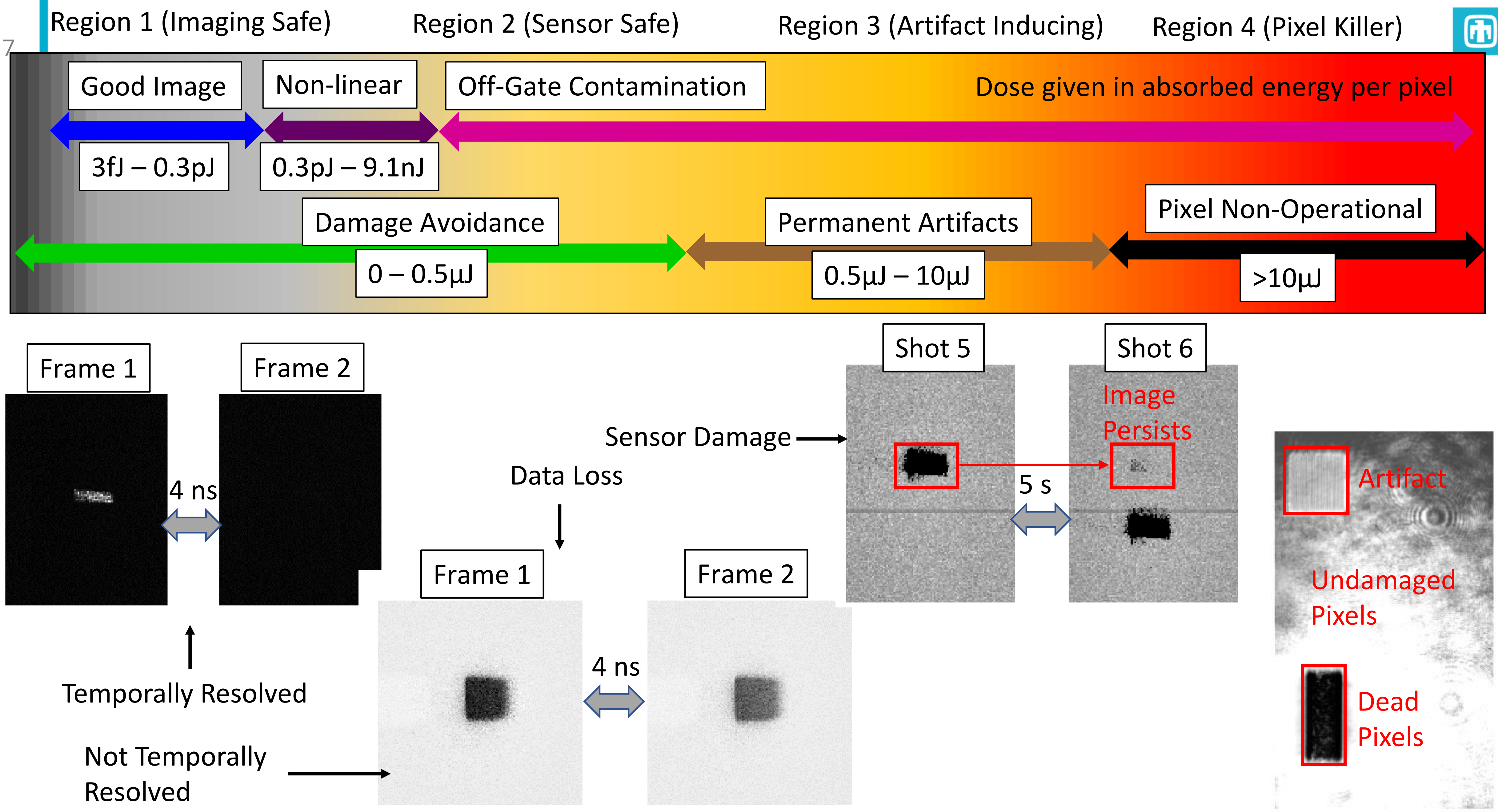
Time-resolved diffraction of dynamically heated Cu at LCLS



P. Hart et al., *Proc. SPIE* 110380Q (2019)

Demo with TX Products WaveGate at PETRA III





Region 1 (Imaging Safe)
Region 2 (Sensor Safe)
Region 3 (Artifact Inducing)
Region 4 (Pixel Killer)
Good Image
Non-linear
Off-Gate Contamination
Dose given in absorbed energy per pixel
3fJ – 0.3pJ
0.3pJ – 9.1nJ
Damage Avoidance
Permanent Artifacts
Pixel Non-Operational
0 – 0.5μJ
0.5μJ – 10μJ
>10μJ
Frame 1
Frame 2
4 ns
Temporally Resolved
Sensor Damage
Data Loss
Frame 1
Frame 2
4 ns
Not Temporally Resolved
Shot 5
Shot 6
Image Persists
5 s
Artifact
Undamaged Pixels
Dead Pixels

The Sandia UXI Family Comprises Nanosecond Gated Sensors

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	Furi	Hippogriff	Icarus V1/V2	Daedalus V1/V2	Tantalus
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CMOS Process	350 nm (SNL)	350 nm (SNL)	350 nm (SNL)	350 nm (SNL)	130 nm (Tower Jazz)
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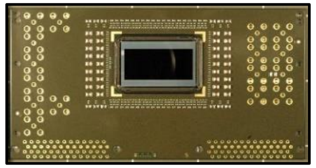
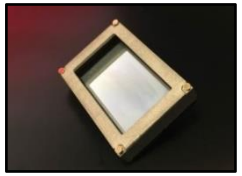
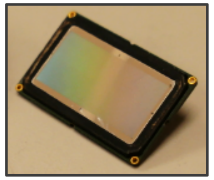
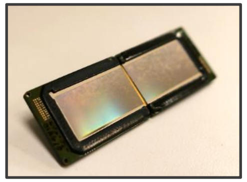
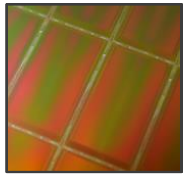
Capacitor Full Well	1.5 million e^-	1.5 million e^-	0.7 million e^-	1.5 million e^-	0.5 million e^-

A review of Sandia's Ultrafast X-Ray Imager Program:
J. L. Porter et al., *Rev. Sci. Instr.* Vol. 94, p. 061101 (2023)

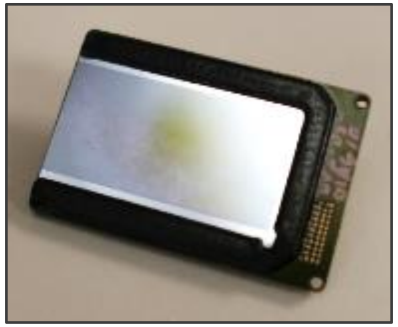
Daedalus is the Newly Completed Addition to the UXI Family

- Highly similar to Icarus in performance and form factor
- Shorter minimum integration time
- Higher full well
- New timing modes added
- Two-detector abutment
- Temperature sensor and corner diode

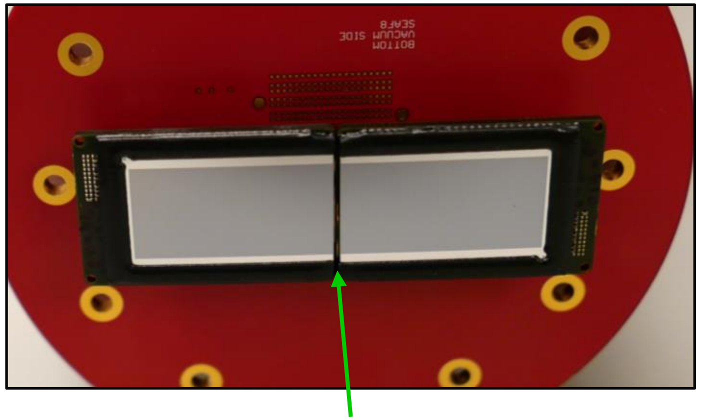
	Icarus	Daedalus
Tech. Node	SNL 350nm	SNL 350nm
# Pixels	1024 x 512	1024 x 512
Pixel Size	25µm x 25µm	25µm x 25µm
# Frames	4 [a]	3 [a,b]
Full well	**700ke$^-$**	**1.5Me$^-$**
Min. gate time	~1.5ns	~1.0ns
Abutment	No	1 short side

[a] Sensor halves can be independently timed
[b] Row interlacing can multiply number of frames

L. Claus et al., *Proc. SPIE* 107630M (2018)



Combined 12.8mm x 51.2mm Area

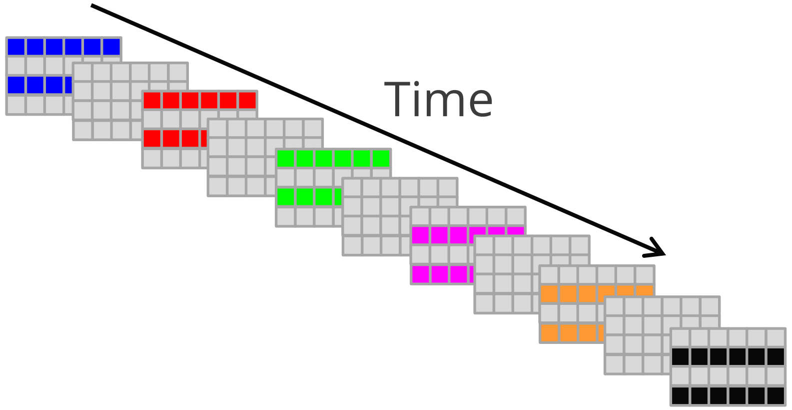


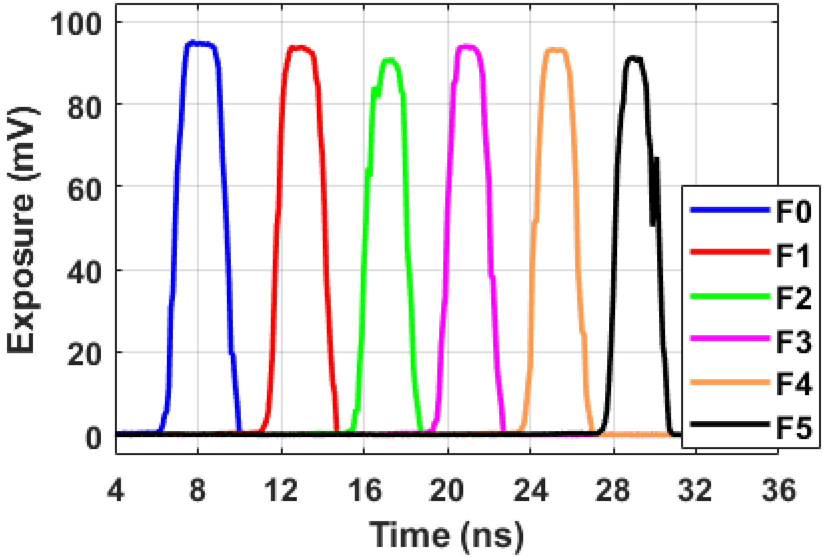
1.25mm Gap

Looker et al., *RSI* 94 113505 (2023)

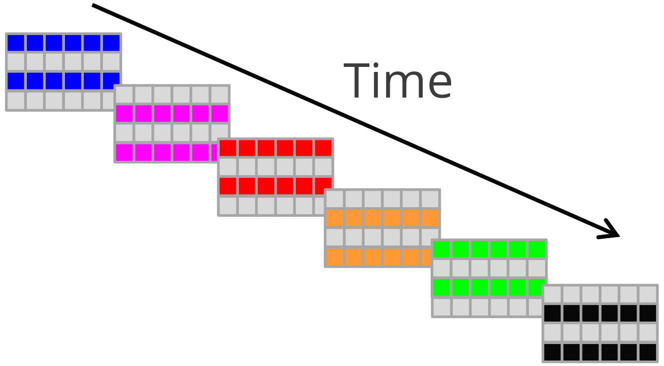
Daedalus Adds New Timing Flexibility

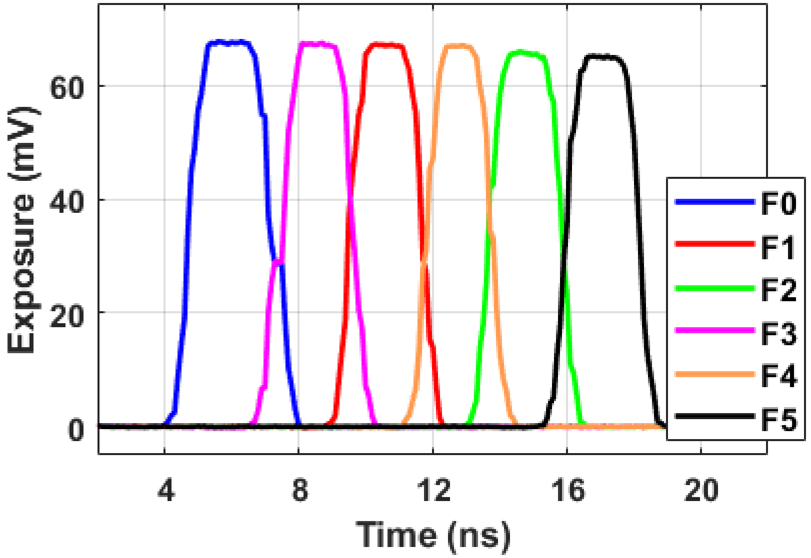
Extend temporal coverage with **row interlacing**



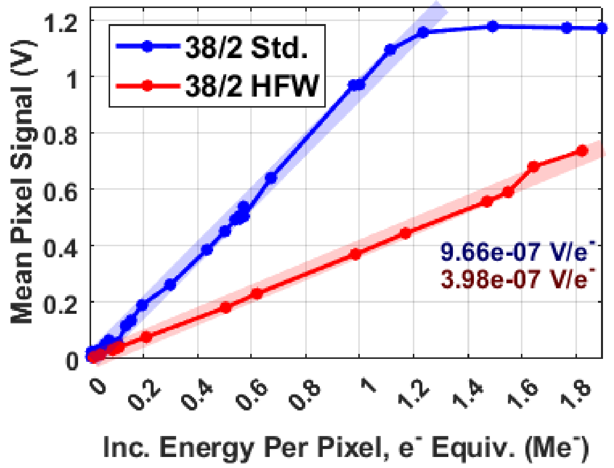


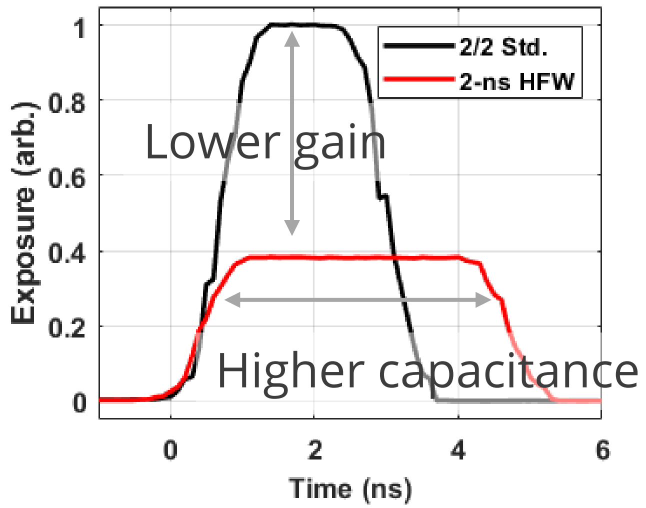
Fill temporal gaps with **zero dead time mode**





Increase full well with **high full well mode**

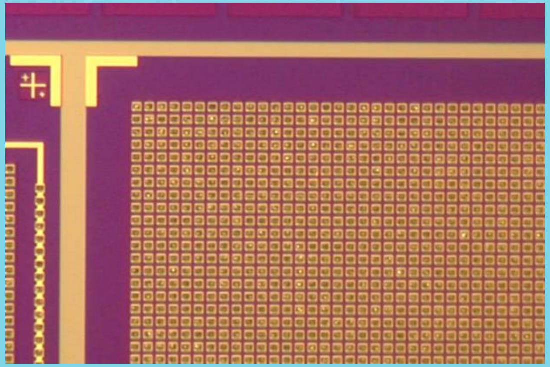


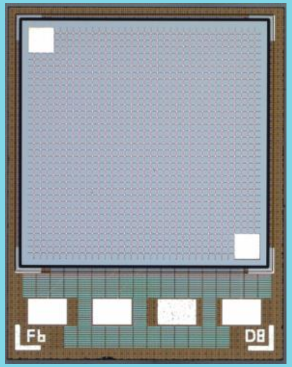


Future Directions

Sensor development

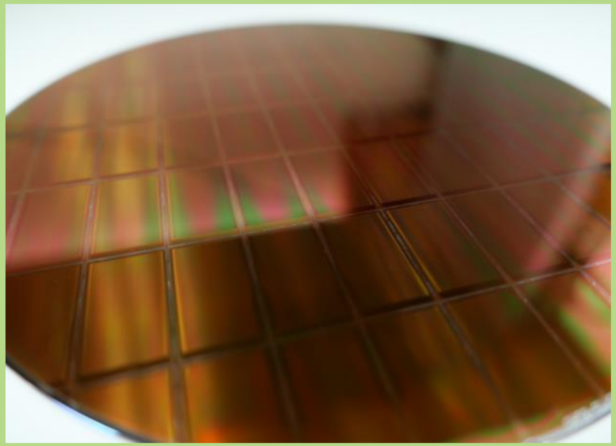
- Faster charge collection
- Higher atomic number





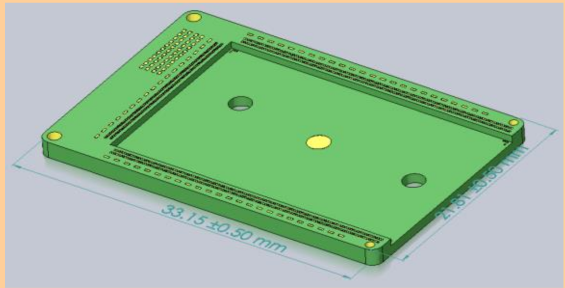
ROIC development

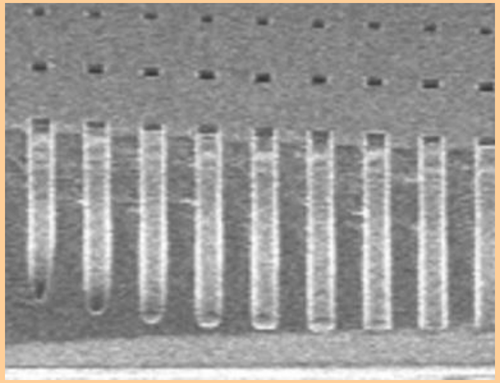
- Faster gate times
- Increased number of frames
- Smaller nodes
- Commercial foundries



Package development

- Improved PCB Design
- Through Si Vias
- Thermal Management

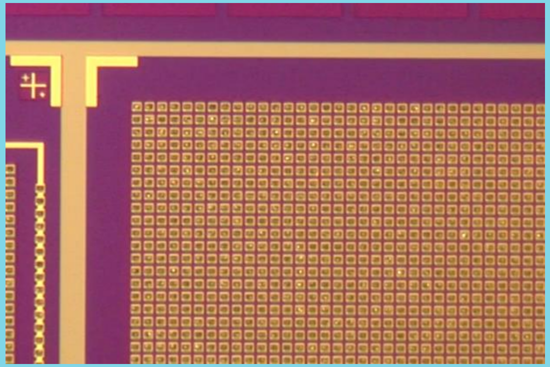


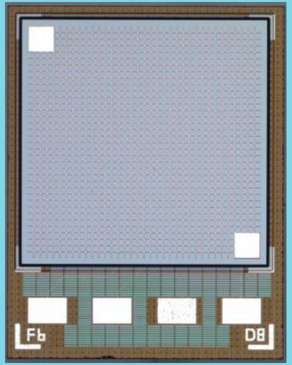


Future Directions

Sensor development

- Faster charge collection
- Higher atomic number





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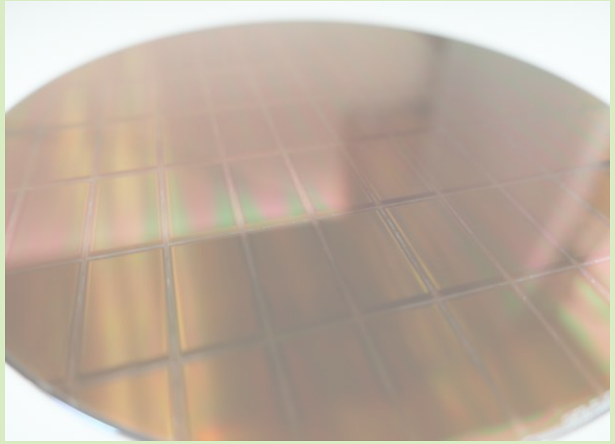
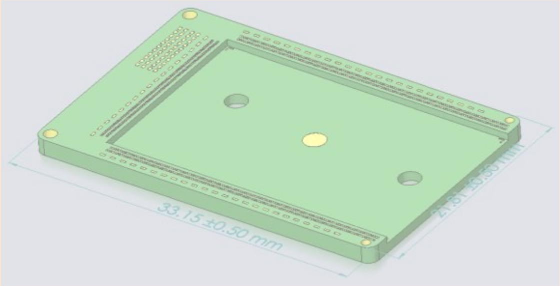
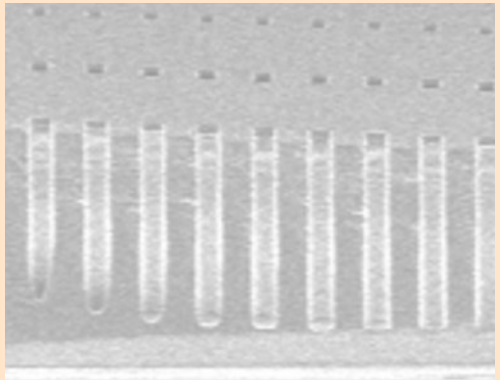


Package development

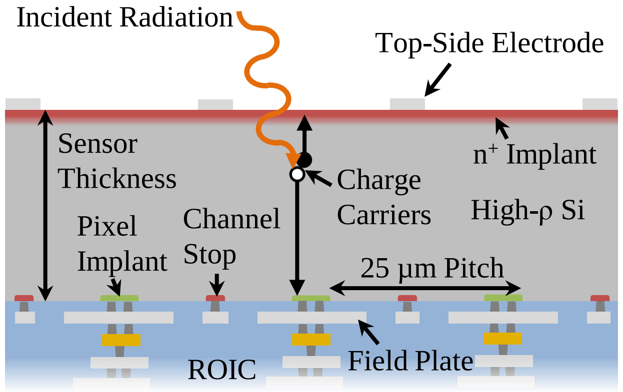
- Improved PCB Design
- Through Si Vias
- Thermal Management

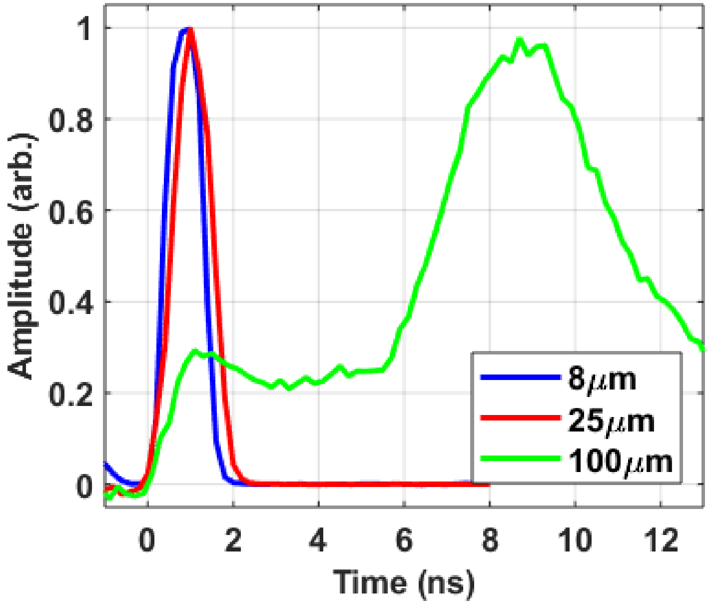




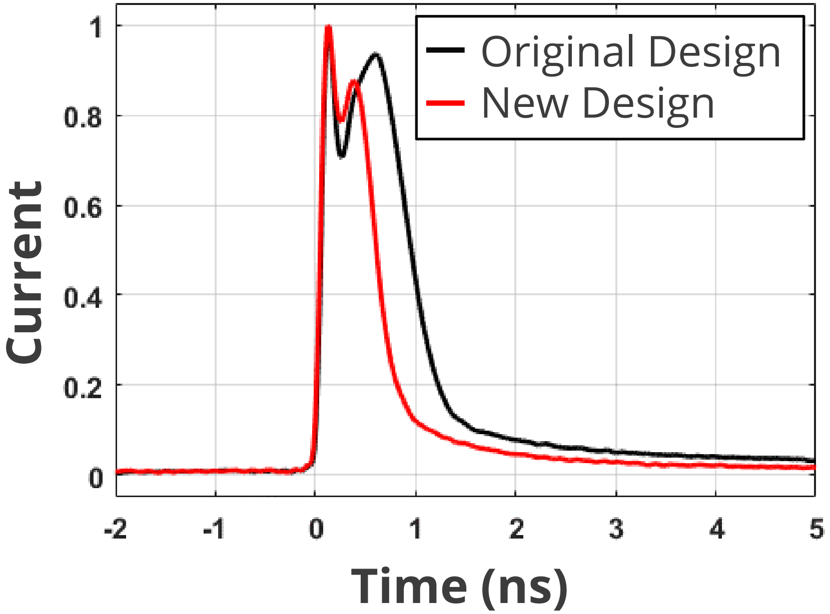
Photodiode Temporal Response Is Now a Limiting Factor

- Overall detector response is convolution of ROIC gate and photodiode current
- With faster ROIC gates, PD current now uncovered as a limiting factor
- Thinner photodiode layer somewhat reduces charge collection time, but also reduces QE
- New PD pixel designs allow sub-ns collection time





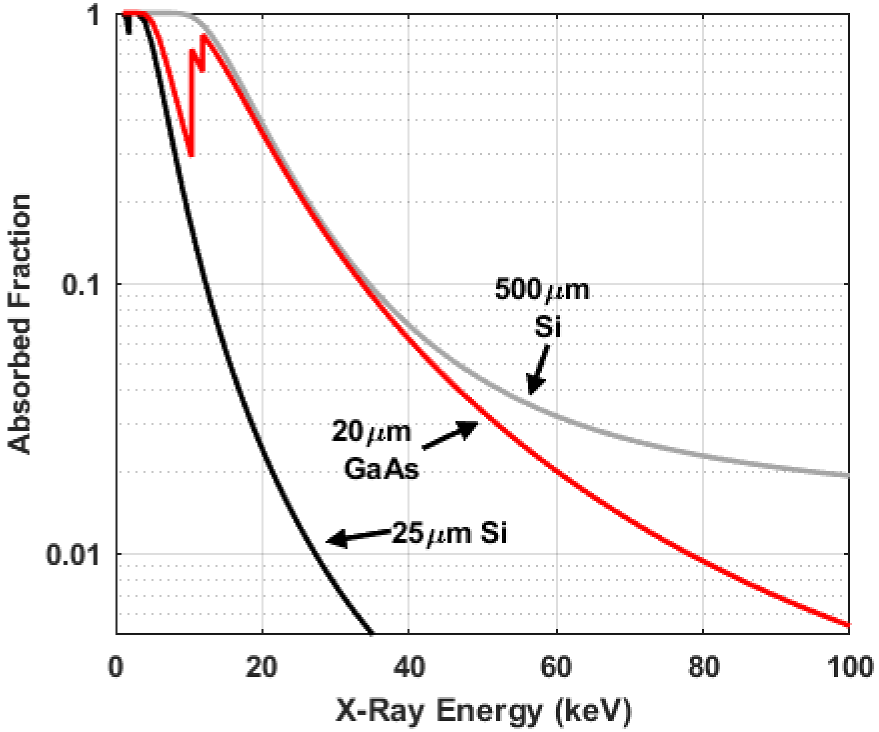
Inferred Photodiode Signal from Gate Profile Deconvolution
Looker et al., *RSI* 92 053504 (2021)

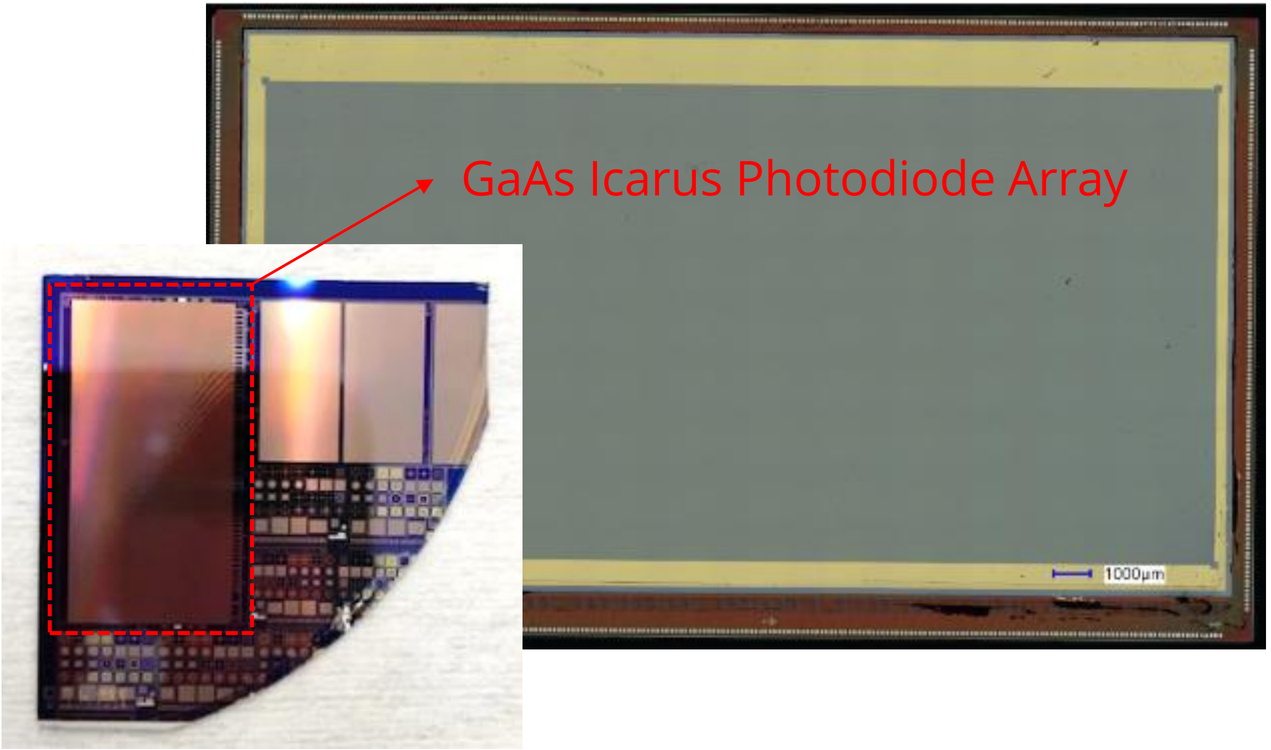


Measured Photocurrent from Test Devices

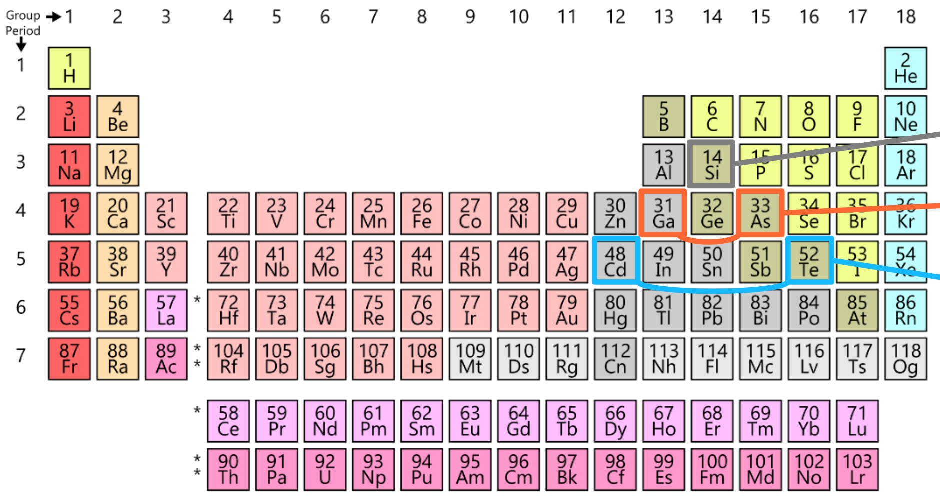
A GaAs Photodiode Array Variant Is Under Development

- Sensor replacement only: 25 μm Si -> 20 μm GaAs
- Identical user experience and performance with enhanced hard X-ray sensitivity
- Fabrication process development underway

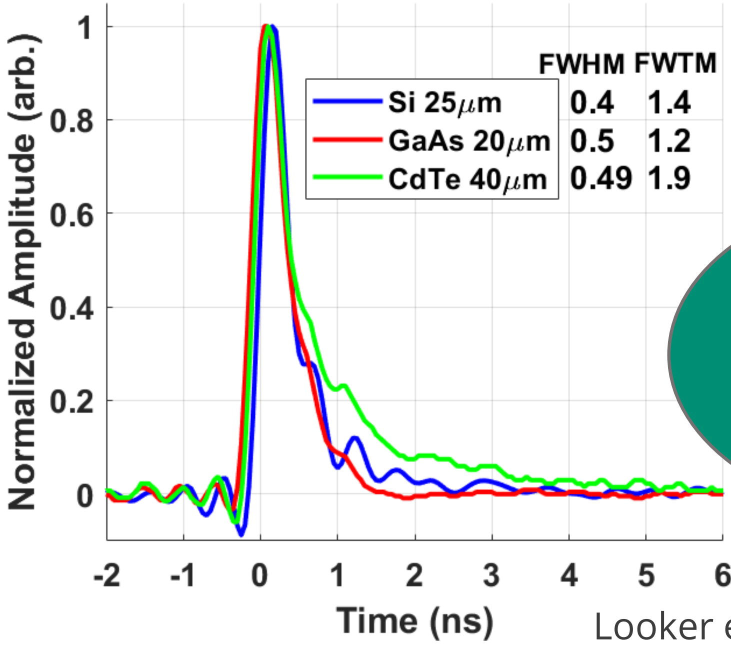




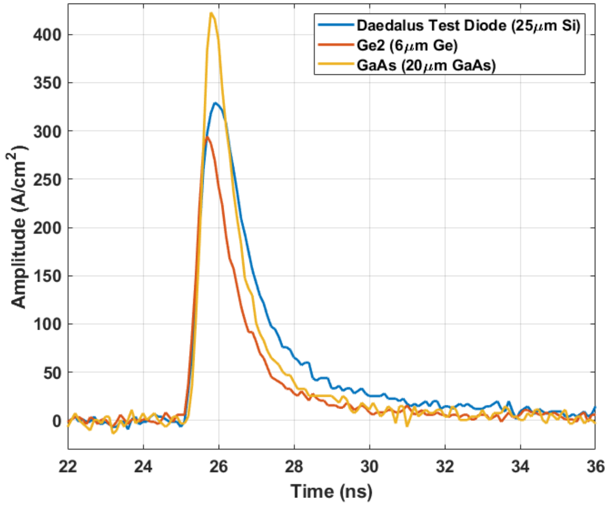
Other detector materials show promise for hard x-ray detectors



Material Investigated	Notes
Si	Mature fabrication, low Z
GaAs	Demonstrated fast detectors
CdTe	Demonstrated fast detectors
Ge	APCVD grown shows promise
CdZnTe	Cannot obtain small detectors
GaN	Background doping too high
PbSe	Thick layers difficult



Detector pulse shapes obtained with Advanced Photon Source white beam

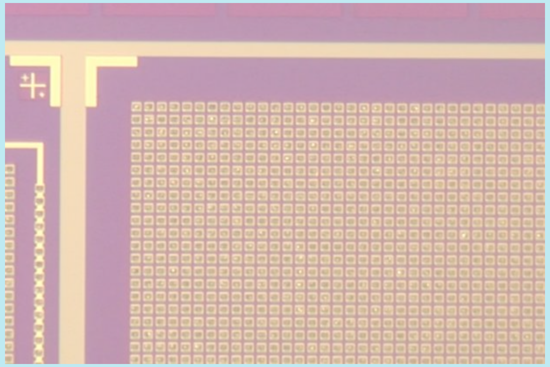


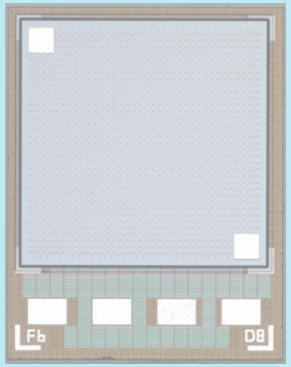
Looker et al., *RSI* 91 023509 (2020)

Future Directions

Sensor development

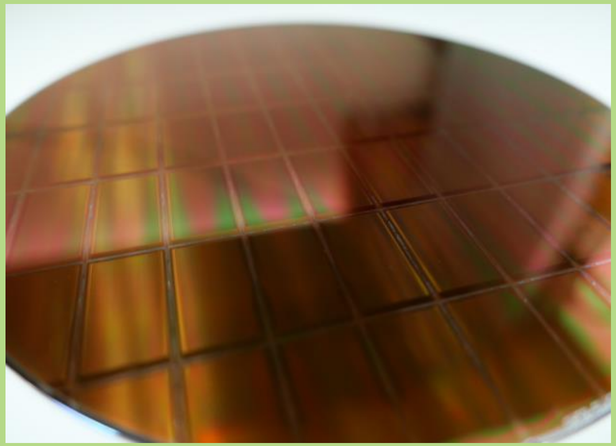
- Faster charge collection
- Higher atomic number





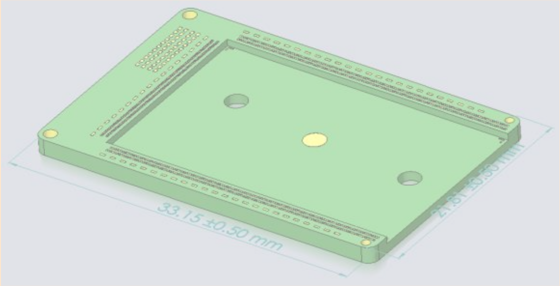
ROIC development

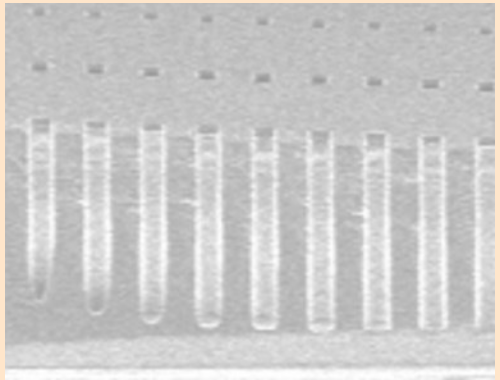
- Faster gate times
- Increased number of frames
- Smaller nodes
- Commercial foundries



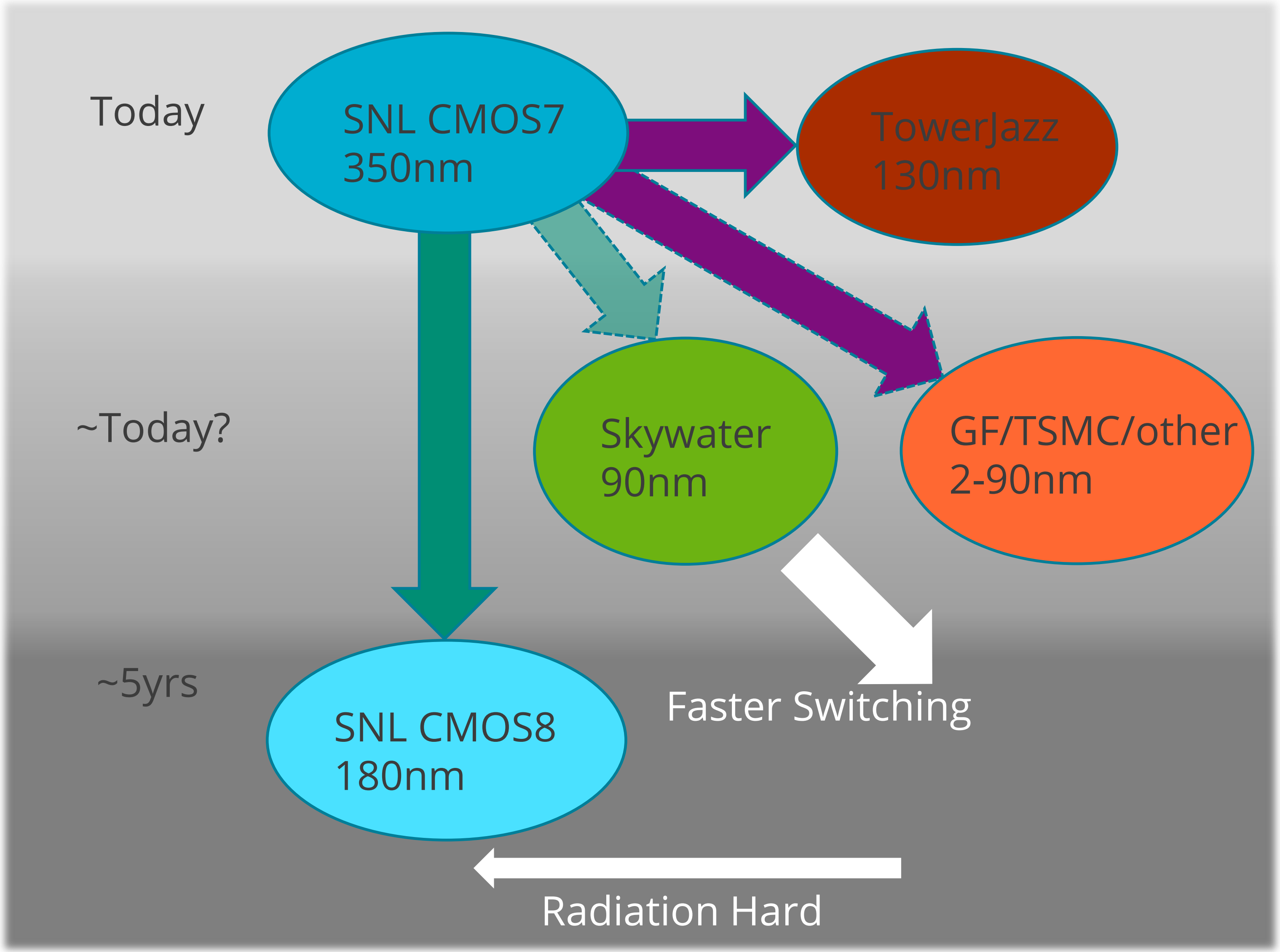
Package development

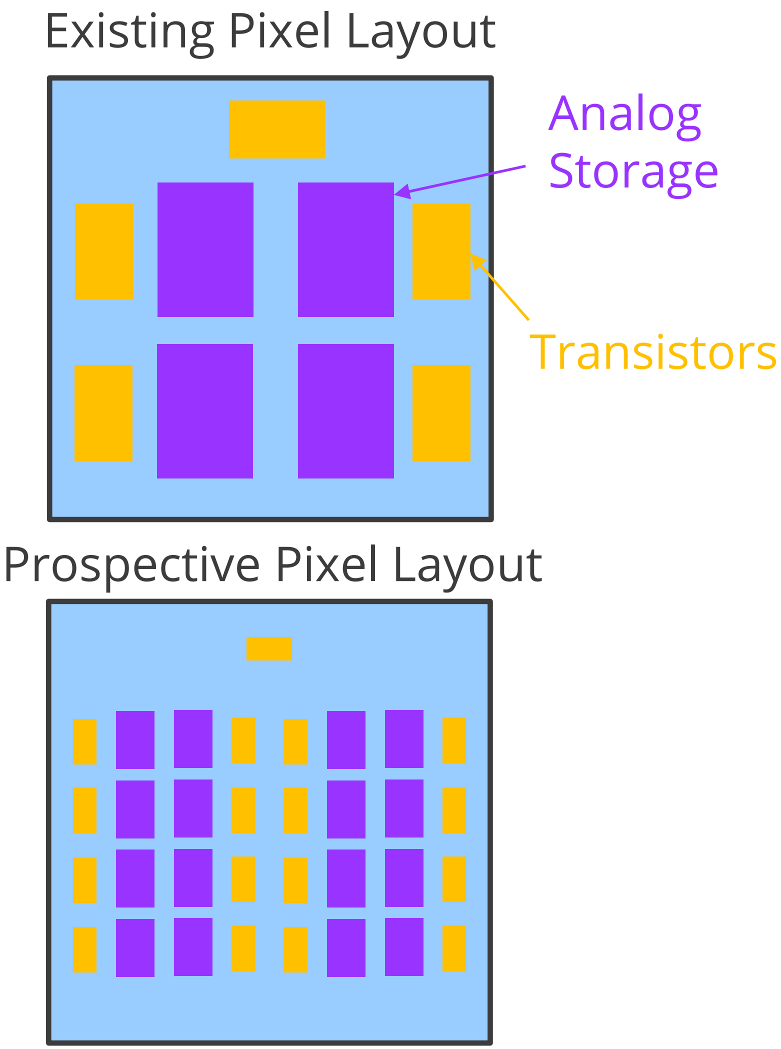
- Improved PCB Design
- Through Si Vias
- Thermal Management





Smaller Nodes May Enable More Frames with Faster Gate Time

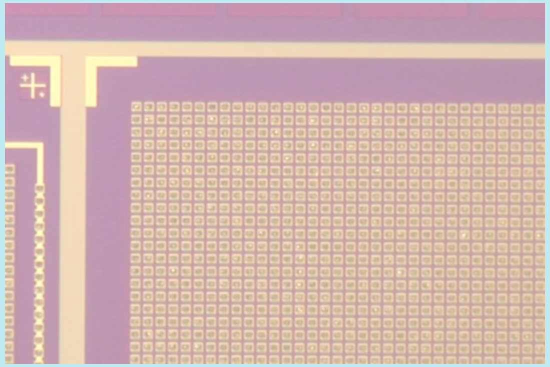


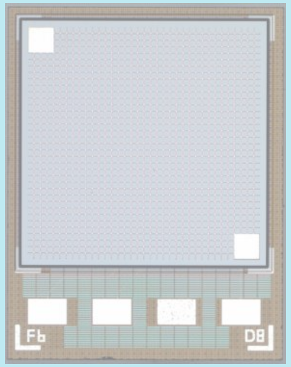


Future Directions

Sensor development

- Faster charge collection
- Higher atomic number





ROIC development

- Faster gate times
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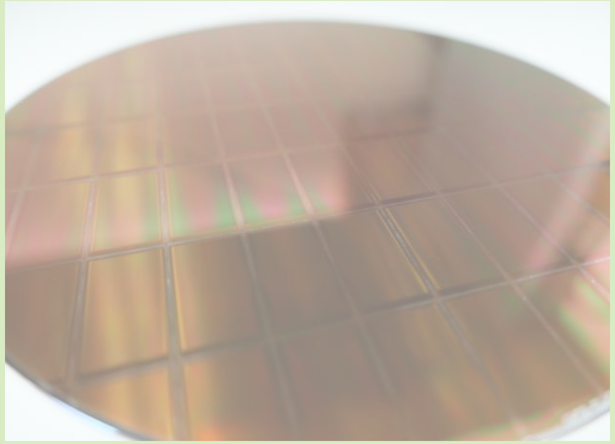
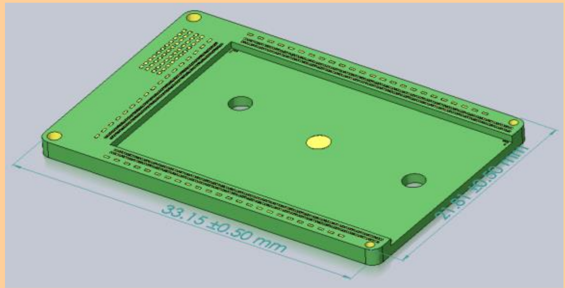
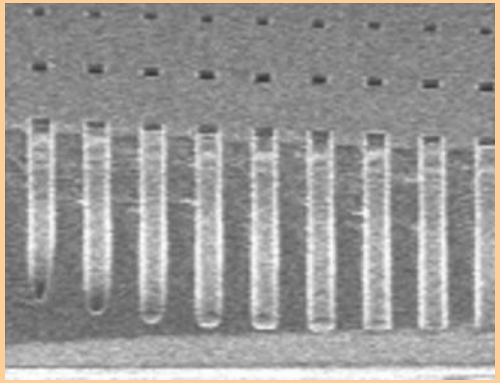


Package development

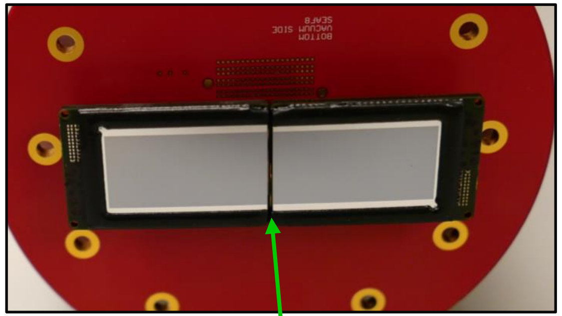
- Improved PCB Design
- Through Si Vias
- Thermal Management





Packaging Improvements Increase Total Image Size and Aid Thermal Stability

Abuttable Modules Multiply Image Area



1.25mm Gap
Combined 12.8mm x 51.2mm Area

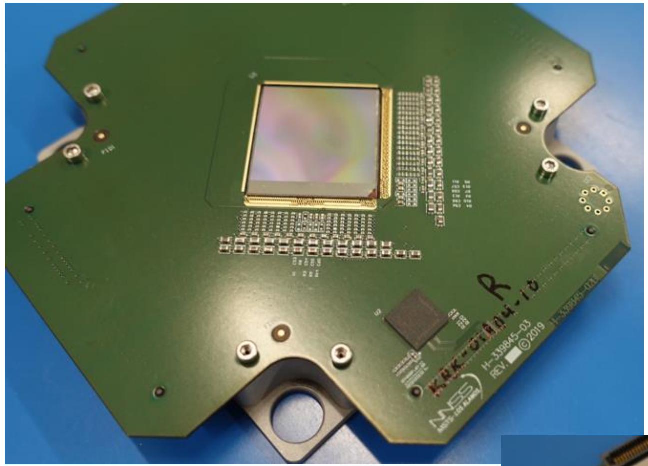
Package Outline

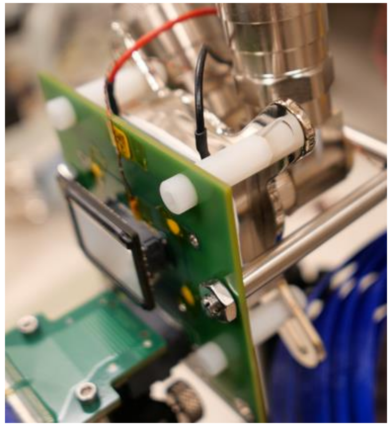
Die Outline

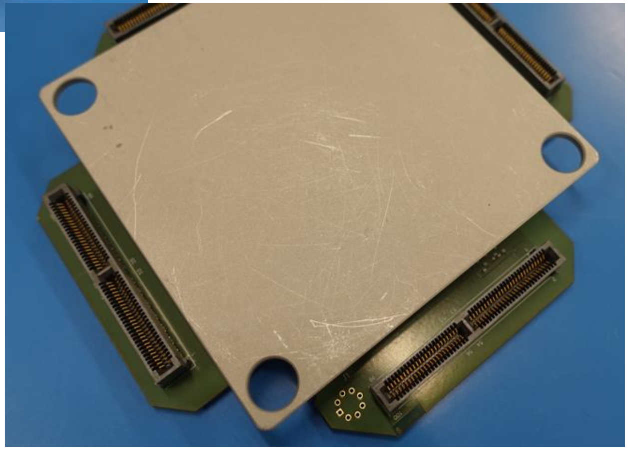
Active Area

Eliminate bond pad periphery with TSVs

Packages with thermal management



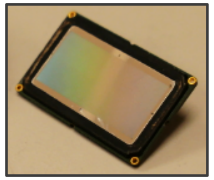
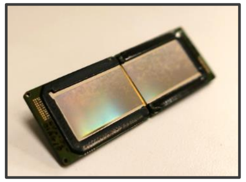
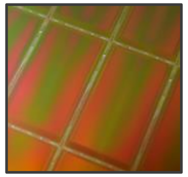




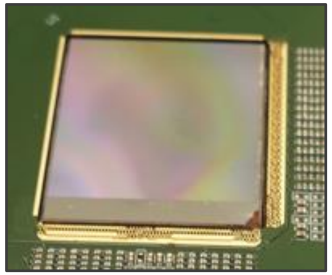
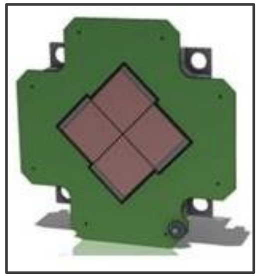
- Lower read noise
- Better timing stability

Summary and Questions

	Deployed	Prototype	In Production
	Icarus V1/V2	Daedalus V1/V2	Tantalus
Year	FY16-18	FY18-23	FY24
Min. Integration time	~1.5 ns	~1.0 ns	~0.5 ns
Frames	4 (full resolution) 8 (L/R interlaced)	3 (full resolution) 6+ (Row/L/R interlaced)	4 (full resolution) 16+ (Row/quad. interlaced)
Tiling Option	No	One Side	No
CMOS Process	350 nm (SNL)	350 nm (SNL)	130 nm (Tower Jazz)
Pixels	512 × 1024	512 × 1024	512 × 1024
Pixel Size	25 μm × 25 μm	25 μm × 25 μm	25 μm × 25 μm
Capacitor Full Well	0.7 million e^-	1.5 million e^-	0.5 million e^-

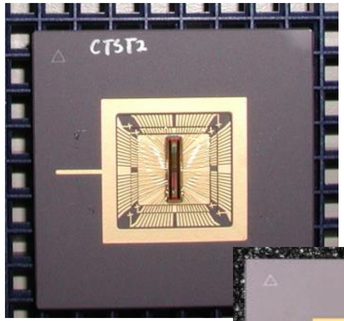
	Prototype	In Production
	Kraken V1	Kraken V2
Min. Integration Time	50 ns	50 ns
Min. Interframe Time	50 ns	50 ns
Effective Dynamic Range	>11 bits (68 dB)	>11 bits (68 dB)
Read Noise	158 e^-	< 100 e^-
Frames	4 (8 without CDS)	8
Pixels	800 × 800 (2 side abuttable)	800 × 800 (2 side abuttable)
Pixel Pitch	30 μm	30 μm
Chip Size	24 x 24 mm	24 x 24 mm
Capacitor Full Well	0.4 million e^-	0.4 million e^-

Other Slides

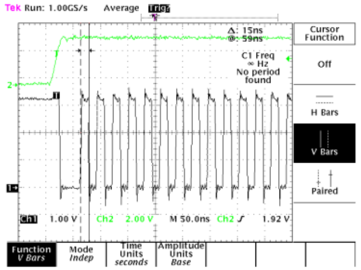
hCMOS Detectors of Today Are the Result of Significant Development

2011

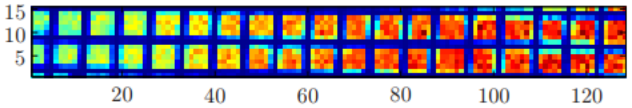


Phoenix

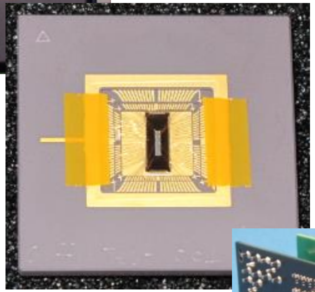
Demonstration of fast onboard timing



X-ray images of wire grid



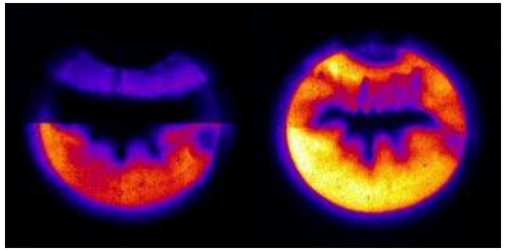
2012



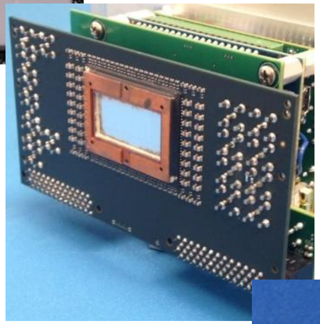
Griffin

Demonstration of x-ray imaging on 128x15 array

GLEH on NIF



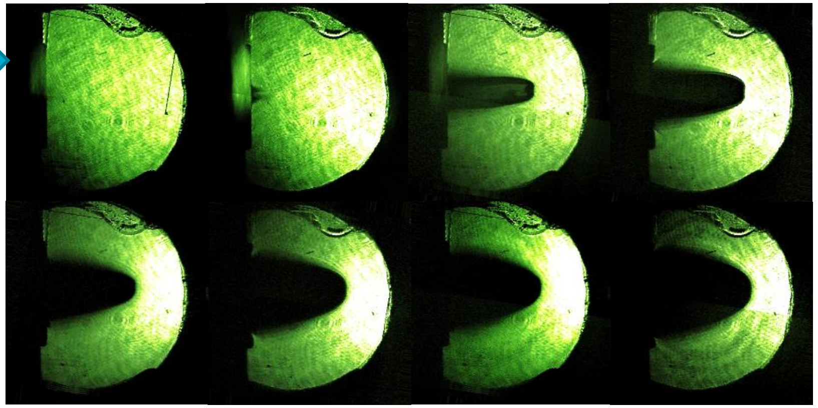
2014



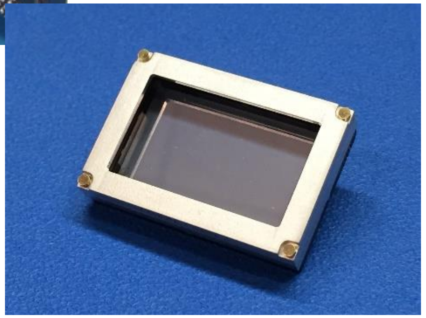
Furi

First full-scale ultrafast x-ray imager

Shadowgraphy of Gas Cell



2015



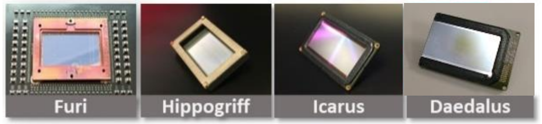
Hippogriff

More frames in a smaller package

A review of Sandia's Ultrafast X-Ray Imager Program:
J. L. Porter et al., *Rev. Sci. Instr.* Vol. 94, p. 061101 (2023)

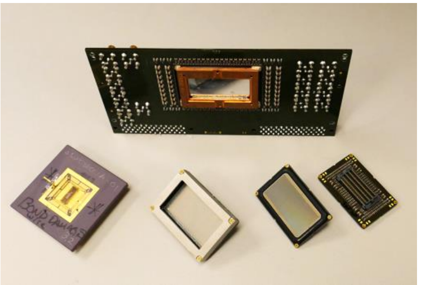
Many Parts and Processes Come Together to Form a UXI Camera

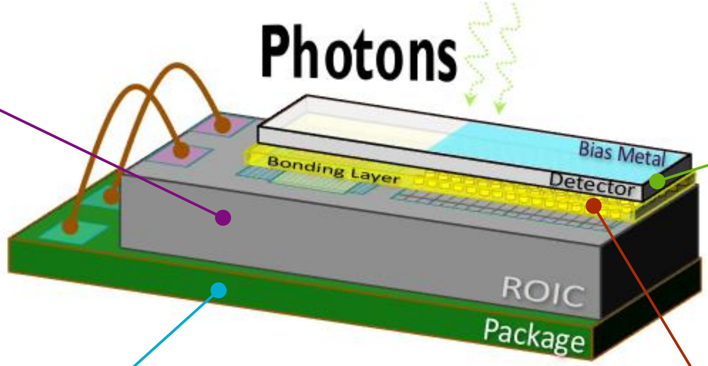
Readout Integrated Circuit (ROIC)



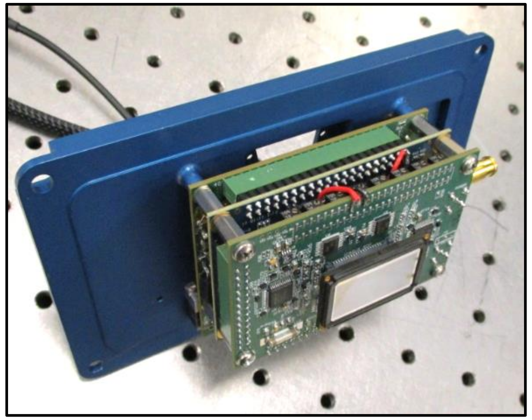
- Fabricated in SNL's 6" 350nm CMOS
- 1-2ns min shutter, 2-8 frames
- 1024x512 array of 25μm x 25μm pixels
- Adjustable shutter timing

Package



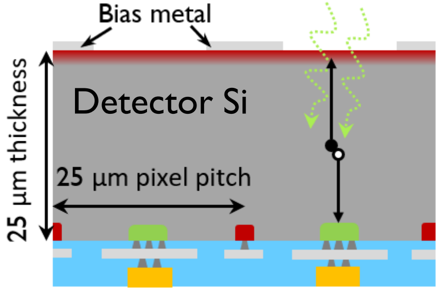


Hybrid CMOS Sensor



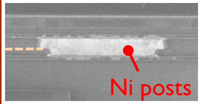
UXI Camera System Development for Application-Specific Needs

Detector Array



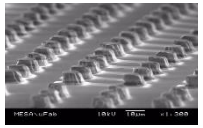
Integration

Direct Bond Interconnect (DBI)



- External supplier
- Wafer-to-wafer bond

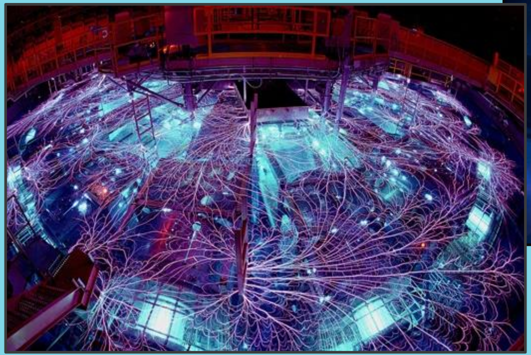
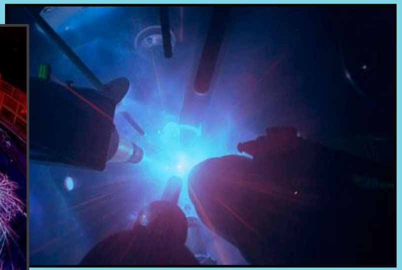
Indium bump



- Processing at Sandia
- Die-level processing

Sandia's Hybrid CMOS Detectors were Developed for Inertial Confinement Fusion and High Energy Density Physics Applications

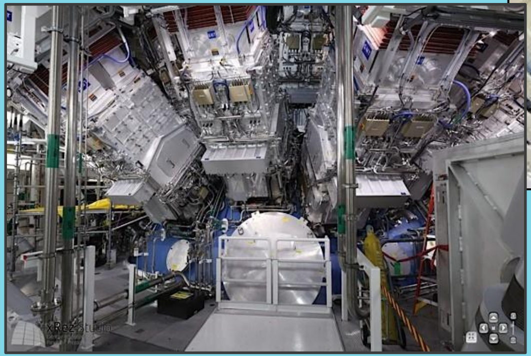
National ICF Facilities

OMEGA LLE

Sandia Z Machine

CEA LMJ



Livermore NIF

- High Intensity (~MJ x-rays, 10^{17} neutrons in ~ns)
- Low Shot Rate (<5 shots/day)

Key Detector Attributes

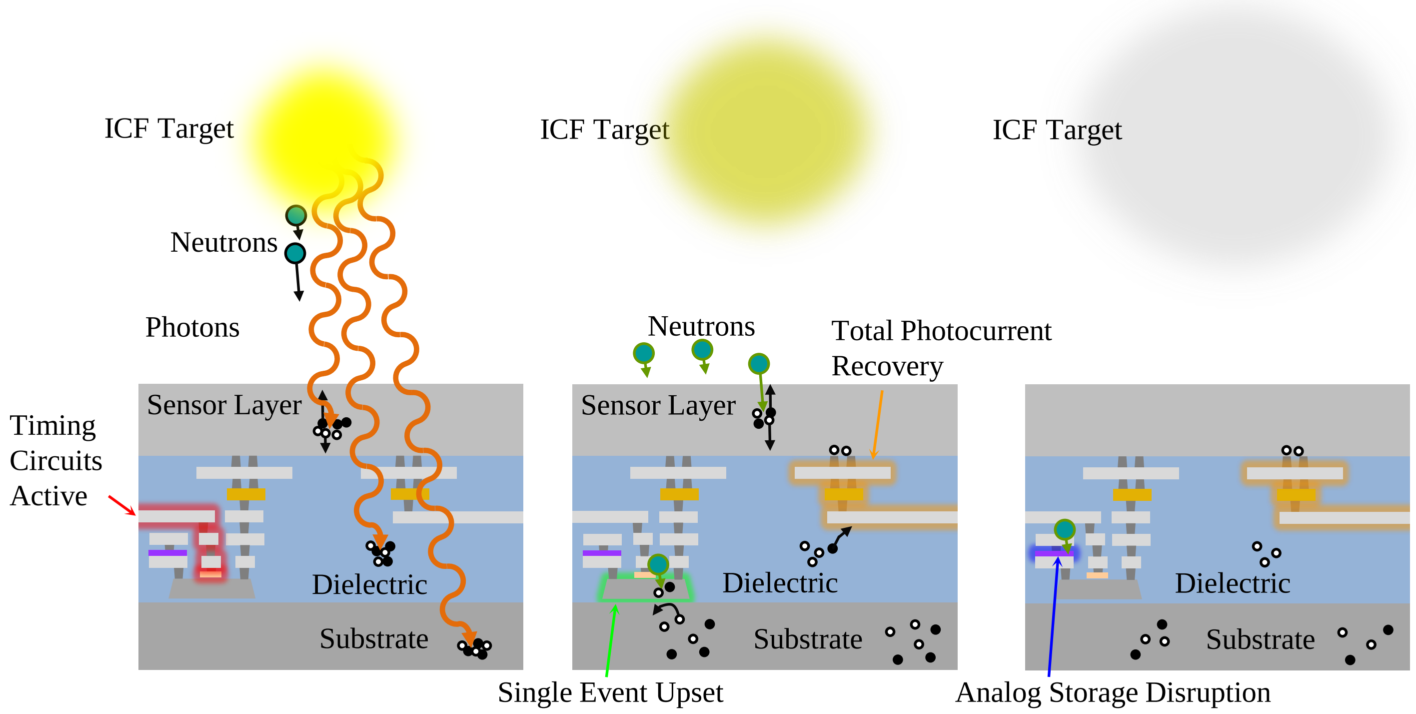
- Radiation Hard
- EMI Resistant
- Selective Sensitivity
- Temporal Resolution
- Shock and Debris Resistance

Tools of the Trade

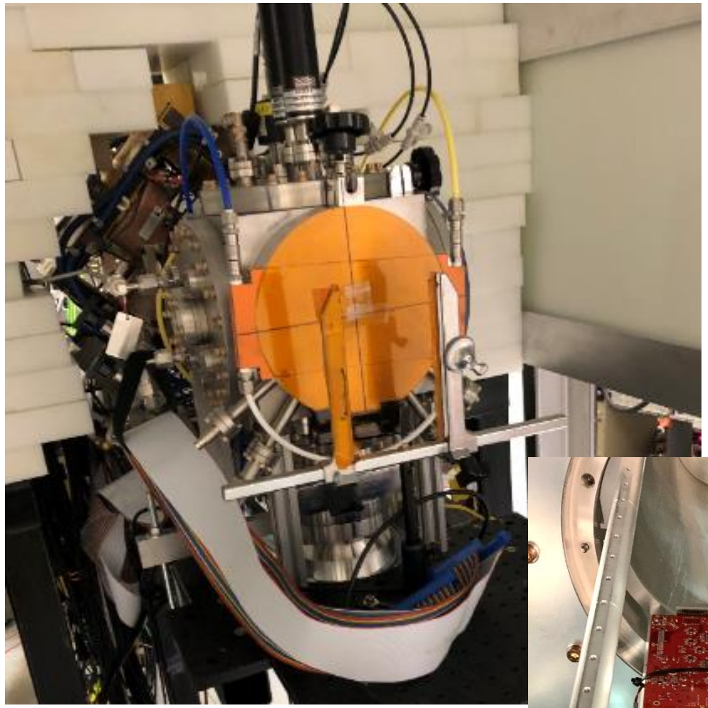
- Photodiodes/PCDs/X-ray Diodes
- Organic Scintillator + PMT
- X-ray Film/Image Plate
- Microchannel Plate
- Streak Camera

hCMOS Detectors are Created With a Radiation Hardened Process

- All detectors in the family are fabricated in Sandia's rad hard CMOS7 350 nm process
- ASIC design minimizes active circuitry during irradiation
- Need to quantify total system tolerance to total neutron dose and single event upsets
- Sandia's Ion Beam Laboratory Irradiation station for NIF-relevant dose of D-D or D-T neutrons
- NIF neutron test well



D-D/D-T Neutron Irradiation Station

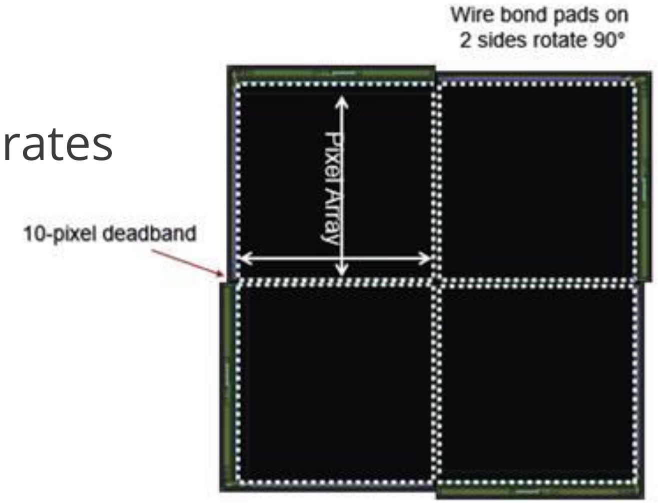


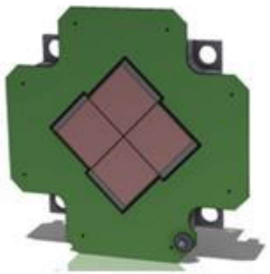
NIF Neutron Test Well

The Related Instrument Line Kraken is Targeted to Multi-Frame Radiography

- Longer integration times
- Lower read noise
- More frames

Kraken V2 incorporates 2-side abutability

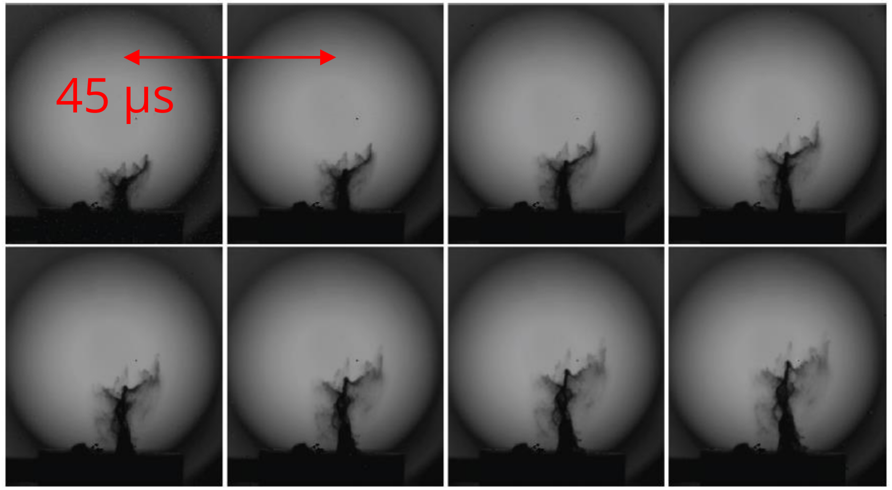




Kraken V1

Item	Specification
Minimum integration time	50 ns
Minimum interframe time	50 ns
Array size	800 × 800 pixels with 2-side abutment
Pixel size	30 µm
Read noise	157 e–
Full well	490,000 e–
Dynamic range	3,130
Sensitivity	5.71 × 10^{12} e–/(J/cm^2)

8-frame Radiograph Set of Laser-Irradiated Silica Beads



Lewis et al., *RSI* 92 083103 (2021)